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Development of an Automated Probe for Thermal Conductivity Measurements

B. P. Dougherty
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Prepared for:
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards and Technology
(Formerly National Bureau of Standards)
Center for Building Technology
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U.S. DEPARTMENT OF COMMERCE
Robert Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
Raymond G. Kammer, Acting Director

Abstract

A transient technique was validated for making thermal conductivity measurements. The technique incorporated a small, effectively spherical, heat source and temperature sensing probe. The actual thermal conductivity measurements lasted 30 seconds. After approximately 15 minutes of data reduction, a value for thermal conductivity was obtained. The probe yielded local thermal conductivity measurements. Spherical sample volumes less than 8 cm^3 were required for the materials tested. Thermal conductivity (and moisture) distributions can be measured for relatively dry or wetted samples.

The technique employs an encapsulated bead thermistor. A thermistor, more commonly used as a temperature transducer, has the inherent feature of being readily self-heated. A computer-based data acquisition and control system regulates the power supplied to the thermistor such that its self-heated temperature response approximates a step change. Thermal conductivity is deduced from the transient measurement of the power dissipated by the probe as a function of time.

The technique was used to measure the thermal conductivity of fifteen liquids and five insulation materials. Two different thermistors types, glass-encapsulated and teflon-encapsulated, were evaluated. Capabilities and limitations of each probe type and the measurement technique, in general, were observed.

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Nomenclature

A = area, m^2

a = probe effective radius, m

B = constant used in equation 16, °C

b = $\left(\frac{k_m}{k_b}\right)\sqrt{\frac{\alpha_b}{\alpha_m}}$, dimensionless

C = $\frac{\Delta T\, R_{t,f}}{V_{ss}^2}$, °C/W

C_p = constant pressure specific heat, J/kg-°C

c = $1 - \frac{k_m}{k_b}$, dimensionless

D = constant used in equation 16, °C/ln(Ω)

e = feedback error, °C

i = current, A

K = feedback gain, mA/°C

k = thermal conductivity, W/m-°C

q = heat transfer rate, W

$\dot{q}$ = power generation per unit volume, W/m^3

R = thermistor resistance, Ω

R^2 = statistical parameter

r = spherical coordinate, m

T = temperature, °C

$\overline{T}$ = $T - T_i$, °C

t = time, s

V = voltage, V

y = variable of integration

Greek Symbols

α = thermal diffusivity, m^2/s

β = transient heat generation constant, $W\text{-}s^{1/2}/m^3$

Γ = steady-state heat generation constant, W/m^3

γ = $\frac{a^2}{\alpha}$, s

ρ = mass density, kg/m^3

σ = $\left(\frac{r}{a} - 1\right)\sqrt{\frac{\alpha_b}{\alpha_m}}$, dimensionless

Subscripts

a = actual

b = thermistor bead, theoretical model

c = correction

d = desired

f = final

i = initial

m = medium

o = output

r = reference

s = surface

ss = steady-state

t = thermistor, physical probe

Introduction

A relatively inexpensive, portable apparatus for in situ thermal conductivity measurements of insulating materials would clearly have a widespread appeal to those concerned with energy conservation and management. This study contributes to the evolution of such an instrument. Thermal conductivity, especially of insulating materials, is rarely measured outside a research or quality control laboratory. A practicing engineer generally relies on data tabulated in handbooks or the manufacturer's literature. Because of the large number of materials and product variability, thermal conductivity data are well documented for only a relatively small sampling of the commercially available insulation products. Moreover, these available values are for new, dry materials rather than for actual installed materials under long term operating conditions. Thus, the design engineer must first categorize a candidate material and then make an allowance, based on experience, for degraded thermal performance resulting from material changes and moisture accumulation. Consequently, significant uncertainty exists in estimating heat transfer through typical insulations using the tabulated thermal conductivity data. An in situ measuring device would provide valuable information on the actual performance of insulation under normal and unexpected operating conditions.

To this end, a transient measurement technique was investigated to determine the thermal conductivity of insulation materials, especially those materials used in solar energy collectors and buildings. The technique incorporates an effectively spherical, small-volume probe that is interfaced with a computer-based data acquisition and control system. The small-volume probe is both an electrical heating element and a temperature sensor. The computer-based data acquisition and control system is used to regulate the probe heating element output and to monitor the probe temperature sensor. In practice, after the small-volume probe is embedded in an insulation material, it is quickly heated in such a way that its temperature response approximates a theoretical step change. The thermal conductivity of the insulation material is deduced from knowledge of how the power dissipated by the probe varies in maintaining the specified temperature rise over time. Transient measurements terminating after 30 seconds yield sufficient information for determining thermal conductivity.

The investigation was divided into key segments. A probe possessing the dual qualities of a heat source and a temperature sensor while having essentially a spherical geometry was needed. Having found one such probe, an experimental apparatus was configured to simulate the analytical model on which the measurement technique is based. The experimental work focused upon integrating the probe and the digital hardware and writing the needed software. The measurement technique was validated using liquids with well-documented thermal conductivities. Liquids with thermal conductivities ranging from 0.1 to 0.6 W/m-°C were used because of a lack of standard reference materials in the range of insulation materials (0.03 - 0.05 W/m-°C). The probe-based measurement apparatus was used to make thermal conductivity measurements of five insulating materials.

Background

The generic designation "small-volume probe" is used even though teflon- and glass-encapsulated bead thermistors exclusively comprise the experimentally evaluated small-volume probes. This preference to discuss the probe in general terms relates to the emphasis given throughout the investigation to building and evaluating the potential of a few types of sensors. In a previous investigation, teflon-encapsulated bead thermistors were used to make local thermal conductivity measurements of a fibrous insulation batt [1]. Thus when this study began, the bead thermistor was viewed as the only probe suited to the measurement application. During the investigation, improved probe configurations were actively sought and several were evaluated. One other probe design, designated the "two-sensor" probe, emerged as worthy of a further, in-depth investigation. The features of this probe are described in a later section. As a result of time constraints, however, the two-sensor probe was not evaluated experimentally.

An encapsulated bead thermistor is suited for the small-volume heating and temperature measurement application. Basically. a thermistor is a resistance-based sensor conventionally employed as a temperature transducer. Thermistors, which are ceramic semi-conductors, can be self-heated. Of the different types of thermistors, bead thermistors more nearly approximate a small sphere. Encapsulation of the thermistor prevents electrical shorting when the probe is submerged in an electrically conducting liquid or embedded in a wetted insulating material.

Thermistor Probe History

The first known investigations using the thermistor probe for thermal conductivity measurements were performed by researchers in the biomedical field. Chato [2] realized that a self-heated bead thermistor could be used to simultaneously measure thermal conductivity and thermal inertia ($k\rho C_p$). Because of an erroneous assumption as to the operation of the thermistor, however, Chato documented values of thermal conductivity with an estimated error of ± 20 per cent. Later, Bowman and his associates at MIT [3] built on Chato's preliminary work. The main accomplishment of the MIT researchers was the development and solution of a more relevant analytical model of the self-heated thermistor probe conducting to a surrounding medium [4,5]. Explicit expressions for two thermophysical properties, thermal conductivity and diffusivity, were formulated given the results from one test.

Once the method had been validated, a range of applications for the new probe were investigated. Among the MIT investigators, Balasubramaniam and Bowman [6] and Valvano et al. [7] quantified the thermophysical properties of different biomaterials. Kravets and Larkin [8] used a self-heated thermistor to measure the thermal conductivity and thermal diffusivity of foods. Woodbury and Thomas [9] incorporated the self-heated thermistor into an investigation to determine indirectly the moisture content of a glass fiber insulation matrix by measuring the material's thermal conductivity.

Probe and Application Innovations

The present work along with that of Woodbury and Thomas and Kravets and Larkin have built upon the findings made in the biomedical field. For example, the biomedical work used relatively small bead thermistors (nominal diameters of 0.75 mm and 1.10 mm). All of the non-biomedical investigations have used the largest, commercially available encapsulated bead thermistors (nominal diameters of 2.54 mm and 2.80 mm). Maximizing the probe's surface area enhances the thermal contact for applications with foods and insulating materials. When self-heated, however, the smaller probes used in the biomedical studies more rapidly approach the desired step temperature response. For biomaterials as well as foods, thermal conductivities ranging from water (0.6 W/m-°C) down to castor oil (0.18 W/m-°C) make up the desired measurement boundaries. Since the present work and the work by Woodbury and Thomas sought to evaluate the thermal conductivity of insulation, the lower bound is reduced to 0.03 W/m-°C.

As compared to the other investigations using the thermistor-based measurement technique, the present work was unique in selected areas. For example, the temperature response of the thermistor was digitally controlled. Analog controllers were used exclusively in all prior investigations. The change to an all-digital system permitted a more efficient data acquisition and reduction procedure. Following a 30-second test, the thermal conductivity of a sample was determined in less than 15 minutes. Only a comparatively small number of materials have been previously tested. Moreover, few materials with known thermal conductivities were used for validating the measurement technique. Twenty-one different materials, most with documented properties, were included in this investigation. As part of this work, the performance differences between a teflon- and glass-encapsulated thermistor were investigated. Kravets and Larkin used glass-encapsulated probes. Woodbury and Thomas used teflon-encapsulated probes. Finally, an investigation into a variation of the thermistor probe (ie., the two-sensor probe) was initiated in this study. No such alternative to the thermistor probe has been previously reported.

A literature review follows. Limited comparisons between the thermistor-based technique and other methods for measuring thermal conductivity are presented. Since thermistors were the only probes experimentally tested, the body of this report focuses on the thermistor-based measurement technique. The analytical model, the test development, and the results of the thermal conductivity measurements are featured. The use of the larger, encapsulated thermistors and the all-digital system used in this study has yet to be validated for measuring thermal diffusivity. For this reason, this report emphasizes the application of the technique for measuring thermal conductivity.

Literature Review

An understanding of the other methods used to make thermal conductivity measurements is beneficial. Obtaining documented thermal conductivity data for calibration and validation purposes is critical. As is discussed later, two properties of the thermistor are determined by conducting calibration tests on materials with known thermal conductivities. Knowledge of the probe's properties is required before the probe can be used to make thermal conductivity measurements of other materials.

Other Measurement Methods

Many methods exist to measure the thermal conductivity of liquids and solids, including insulation materials. Three comprehensive sources for expanded, albeit selective, presentations of the more common methods are references 10,11, and 12. Many technical papers are concerned with only one method [13,14,15,16,17]. With respect to the development of the thermistor probe, an understanding of four particular methods -- the guarded hot plate, the flat-screen tester, the transient hot-wire, and the line source probe -- was judged to be important.

A review of the methods used for measuring the thermal conductivity of insulation revealed that the two dominating are the guarded hot plate [18] and the flat-screen tester [19]. Both apparatuses are configured to promote one-dimensional conductive heat flow. The guarded hot plate is a steady-state measurement technique while the flat-screen tester is a transient measurement device. The accepted guarded hot plate standard is housed at the National Bureau of Standards in Gaithersburg, Maryland. This standard apparatus is reported to measure the apparent thermal conductivity of low-density, glass-fiber insulation with an uncertainty of less than 1 per cent [20]. For similar materials, the Oak Ridge National Laboratory flat-screen tester possesses a measurement uncertainty of ± 1.7 per cent [21].

The probe-based technique and the two established, absolute measurement techniques would act in complementary roles. The guarded hot plate and the flat-screen tester would be used to first accurately measure the thermal conductivity of particular materials, some possibly being accepted as standard reference materials. These materials would be used to calibrate the thermistor probe. The probe would then act as a secondary standard in the field where cost and lack of mobility exclude the use of the two primary methods.

The transient hot-wire and the line source designate two different types of apparatus. Both methods are based, however, on the same analytical model. This model consists of an infinitely long line source conducting to an infinite, isotropic medium. The infinite line source effects a constant heat flux boundary condition on the surrounding medium. In practice, the temperature rise of the line source or hot-wire is measured as a function of time during the heating process. The thermal conductivity of the surrounding test medium is determined from the slope of the linear plot of the temperature rise vs the natural logarithm of time [22] The differences between the transient hot-wire apparatus and the line source probe stem from their respective constructions. The transient hot-wire is constructed to promote high measurement accuracy while the line source probe is configured to provide in situ measurement capabilities.

For the transient hot-wire apparatus, a precision resistance wire acts as both the heating element and the temperature sensor [23]. This resistance wire stretches along the centerline of a sealed vessel. The test material, usually a liquid or gas, is poured into the vessel and then heated or cooled to a desired uniform temperature. Once the sample has reached thermal equilibrium, the hot-wire is heated, and the transient temperature measurements begin. Total data acquisition times range from one [24] to ten seconds [25]. The short test interval, along with physical modifications to the apparatus and mathematical corrections, helps to minimize natural convection, radiation, and stray conduction losses [26,27,28]. Thermal conductivity measurements of liquids using transient hot-wires are subject to overall uncertainties ranging from ± 0.5 per cent to ± 1.5 per cent [10]. The transient hot-wire, which lacks in situ measurement capabilities, would complement the thermistor-based measurement technique in the same way as the guarded hot plate and the flat-screen tester.

For a typical line source probe, a separate resistance heating wire and a temperature sensor are encapsulated in a metal sheathing. The temperature sensor, either a thermocouple [29] or a thermistor [30], is positioned at the midpoint of the cylindrical probe. Because the probe is rigid and is sealed, it may be used with liquids or solids. Total data acquisition times may range from 30 seconds to 15 minutes. Only a relatively small window of this total time, however, is typically used to determine the thermal conductivity of a sample [31]. With respect to this window of pertinent data, Drotning and Tormey [32] report that an incorrect result is possible if the first of two linear regions of the characteristic plot (ie., temperature rise versus the natural log of time) is used. Thermal conductivities accurate to ± 4 per cent have been reported by Asher [30] for a line source probe (referred to as a transient needle probe in his work). Like the thermistor, a line source can be used for making in situ thermal conductivity measurements for insulating materials [33,34].

The line source probe and the thermistor probe technique each have distinct advantages and disadvantages. For example, the thermistor makes only relative measurements. In comparison, the line source probe can make both relative and absolute measurements [30]. An absolute measurement technique is preferred because calibration is not required [10].

Moreover, when the application requires that the line source be calibrated (to account for the finite heat capacity and thermal conductivity of the probe), only one reference material is needed [30]. The thermistor probe, on the other hand, requires at least two reference materials for calibration. A preferred characteristic of a small thermistor probe is its ability to approach a point measurement. The thermal conductivity of a sample as measured by a line source, on the other hand, is a value averaged over the length of the probe as well as radially. Because probe operation is based on conducting to an isothermal medium, the line source probe is not suited for applications in materials where a temperature gradient exists. Consequently, a thermistor probe is better suited to measure the thermal conductivity of insulation in an exterior wall or ceiling. Finally, with the thermistor-based technique, thermal diffusivity can also be determined from the same test. The line source probe is not known to have been used to measure thermal diffusivity.

Reference Materials

The search for appropriate reference materials (ie., materials with well-documented and readily repeatable thermal conductivities) began at the inception of this investigation and still continues. Because the thermistor probe cannot readily penetrate dense solids, the group of applicable reference materials is comprised of liquids, soft solids like fibrous insulation, and substances which can be molded around the probe. Materials with thermal conductivities less than that of water (0.6 W/m-°C) are sought. Suitable materials with thermal conductivities bracketing the range of test specimens are also essential.

Some reference materials have been investigated by a number of researchers while others by only one. Using a transient hot-wire apparatus, Nieto de Castro, et al. [35] and Takizawa, et al. [36] measured the thermal conductivity of a variety of liquids, including distilled water, toluene, n-heptane, glycerin, ethyl alcohol, acetone, and methanol. A line source probe was employed by Asher [30] to measure the thermal conductivity of tert butanol. Touloukian et al. [11] combined the work of many workers and published the most extensive compilation of thermal conductivity data. Many other sources document thermal conductivity data for a range of different materials [37,38,39,40,41,42,43,44,45].

Uncertainties in reported property values for reference materials exist. Differences in some reported values are significant. For example, of four sources listing the thermal conductivity of ethylene glycol [11,43,46,47], values for a temperature of 25°C range from 0.251 [46] to 0.283 W/m-°C [43], a 13 per cent difference. Moreover, two sources [11,46] report that the thermal conductivity of ethylene glycol increases with temperature while the other two sources [43,47] report the opposite trend. With any material for which more than one source was identified, the author attempted to pick the best value based on the method used and the most recent work. For the cases based on a single source, the reported values are used but it is recognized that experimental error is likely.

Analytical Model: Thermistor Probe

The encapsulated thermistor approximates the ideal small-volume probe. Besides possessing the dual capablities of heating and temperature sensing, an ideal probe would have a negligible mass and a spherical shape, would be electrically insulated, and the measured temperature would be that of its isothermal surface. The operation of the thermistor departs from the ideal. For example, the surface temperature of the thermistor's encapsulation is not measured; instead, the measured temperature corresponds to a volume-averaged value for the thermistor bead. The temperature gradient within the thermistor must be taken into account in the analytical model. The resulting heat transfer problem is one with coupled heat conduction equations.

Coupled Heat Conduction Equations

The analytical model on which the measurement technique is based takes into account the time-dependent temperature distributions in both the encapsulated thermistor and the surrounding medium. This analytical model is mathematically expressed by equations 1 and

2. The heat transfer mechanism is assumed to be pure conduction. The thermistor bead and the encapsulation (pictured within a later section on the experimental apparatus) are aggregated and modelled as a perfect sphere of radius a with constant thermal conductivity, k_b , and thermal diffusivity, α_b. The surrounding medium is modelled as isotropic and infinite while having similarly constant thermophysical properties, k_m and α_m. Heat generation per unit volume within the thermistor, $\dot{q}(t)$, is assumed to be spatially uniform. Throughout the mathematical analysis, the subscript b identifies properties of the bead thermistor while the subscript m denotes variables associated with the surrounding medium.

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial T_b}{\partial r}\right]+\frac{\dot{q}(t)}{k_b}=\frac{1}{\alpha_b}\frac{\partial T_b}{\partial t} \qquad 0\leq r\leq a \qquad (1)$$

$$\frac{1}{r^2}\frac{\partial}{\partial r}\left[r^2\frac{\partial T_m}{\partial r}\right]=\frac{1}{\alpha_m}\frac{\partial T_m}{\partial t} \qquad r\geq a \qquad (2)$$

Four boundary conditions accompany these coupled heat conduction equations.

symmetry:

$$\frac{\partial T_b}{\partial r}(0,t)=0 \qquad t>0 \qquad (3)$$

no contact resistance:

$$T_b(a,t)=T_m(a,t) \qquad t>0 \qquad (4)$$

energy balance:

$$k_b\frac{\partial T_b(a,t)}{\partial r}=k_m\frac{\partial T_m(a,t)}{\partial r} \qquad t>0 \qquad (5)$$

infinite medium:

$$T_m(\infty,t)=T_i \qquad t>0 \qquad (6)$$

Initially, the temperature throughout the thermistor and the surrounding medium is constant, ie.,

$$T_b(r,0) = T_i \qquad 0 \leq r \leq a \quad (7)$$

$$T_m(r,0) = T_i \qquad r \geq a \quad (8)$$

In order to solve for the temperature distributions, the form of the heat generation function, $\dot{q}(t)$, must be determined. The approach used for making this determination follows.

Heat Generation Function

Three different approaches have been previously used to show that in order to achieve a step temperature change the heat generation per unit volume must vary linearly with the inverse square root of time

$$\dot{q}(t) = \Gamma + \beta t^{-1/2} \qquad t > 0 \quad (9)$$

where Γ and β are referred to as the steady-state and transient constants, respectively. Woodbury [1] showed that in order to effect a step change on the surface of the thermistor bead -- an ideal condition -- the bead must dissipate power according to equation 9. Assuming that the function is composed of a constant plus a transient term, Valvano [5] deduced the form of the transient term, $\beta t^{-1/2}$. These two analytical approaches explained what had first been experimentally ascertained by Balasubramaniam and Bowman [4,6].

An experimental approach confirmed that the encapsulated thermistors used in this study generate heat in accordance with equation 9. Typical temperature response curves for the glass- and teflon-encapsulated thermistors dissipating heat to glycerin are given in Figs. 1 and 2. The glass-encapsulated thermistor completes its initial transient response in slightly

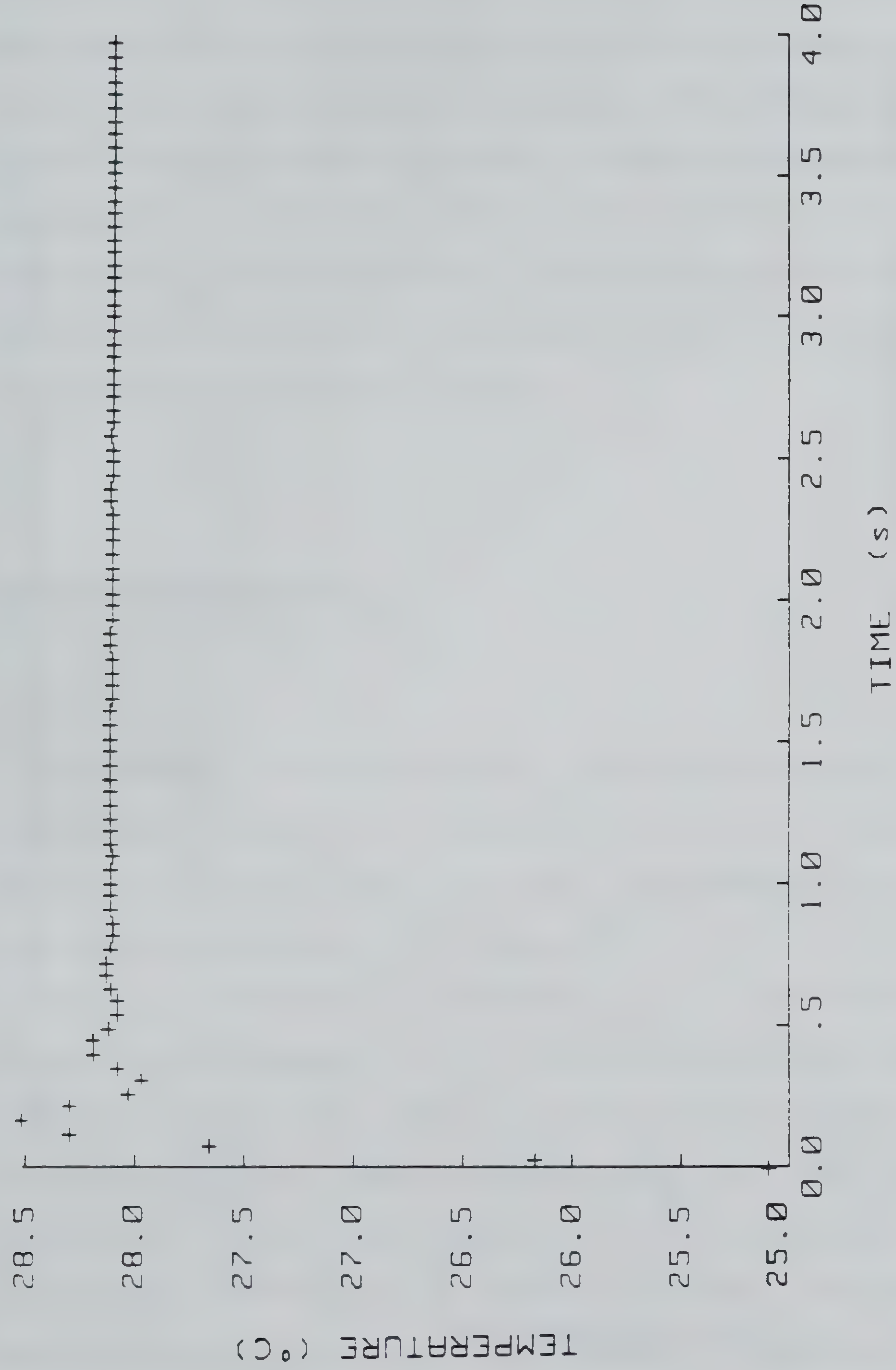


Figure 1. Typical Temperature Response for the Self-heated Glass-encapsulated Thermistor

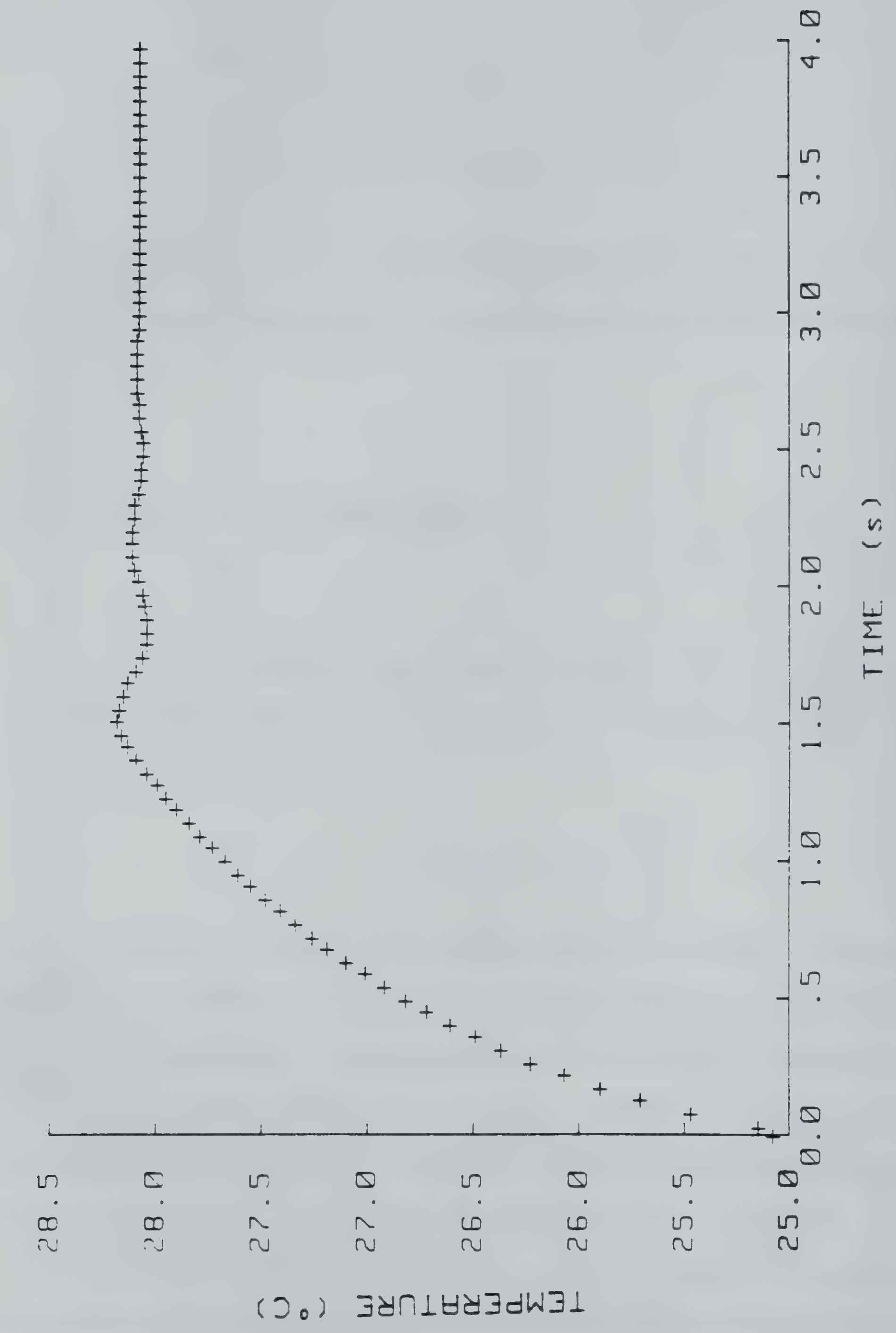


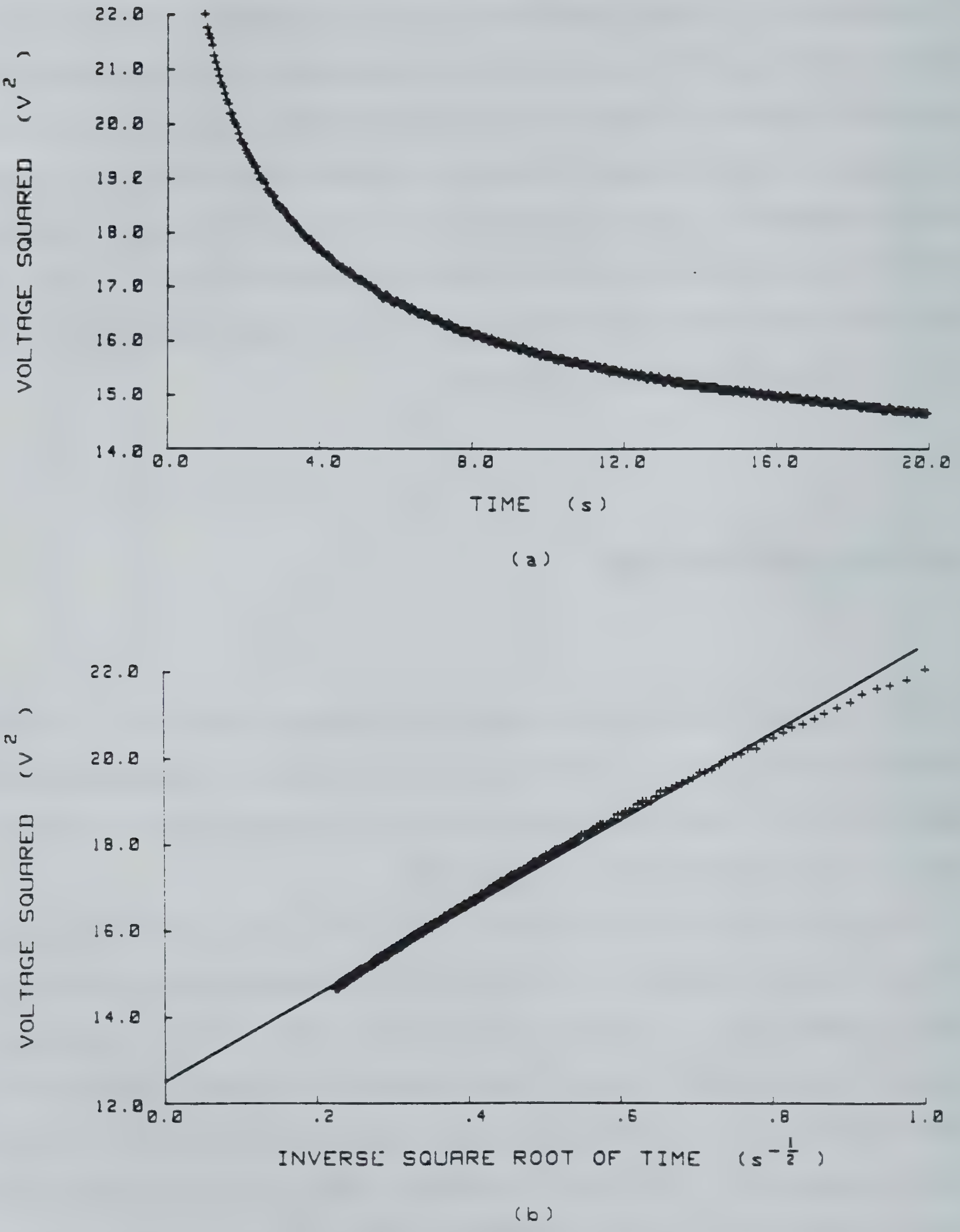
Figure 2. Typical Temperature Response for the Self-heated Teflon-encapsulated Thermistor

over a second whereas the teflon-encapsulated thermistor requires approximately 3 seconds. The mechanism for controlling the thermistor temperature response is described later. As shown in Figs. 3(a) and 4(a), once the desired temperature rise is obtained the power, here expressed as the voltage squared, decreases rapidly with time. (Voltage squared is directly proportional to the power because the resistance is constant corresponding to the controlled elevated temperature.) Plots of the voltage squared versus the inverse square root of time exhibit the expected linear characteristic for both the glass-encapsulated, Fig 3(b), and the teflon-encapsulated thermistors, Fig. 4(b). The y-intercept and slope from these linear plots are directly proportional to Γ and β, respectively.

Solution Methodology

The procedure for solving the coupled heat conduction equations is qualitatively described. The final expressions for the temperature distributions in the aggregate thermistor bead and the surrounding medium are included. The complete solution is detailed by Balasubramaniam and Bowan [4] and by Valvano [5].

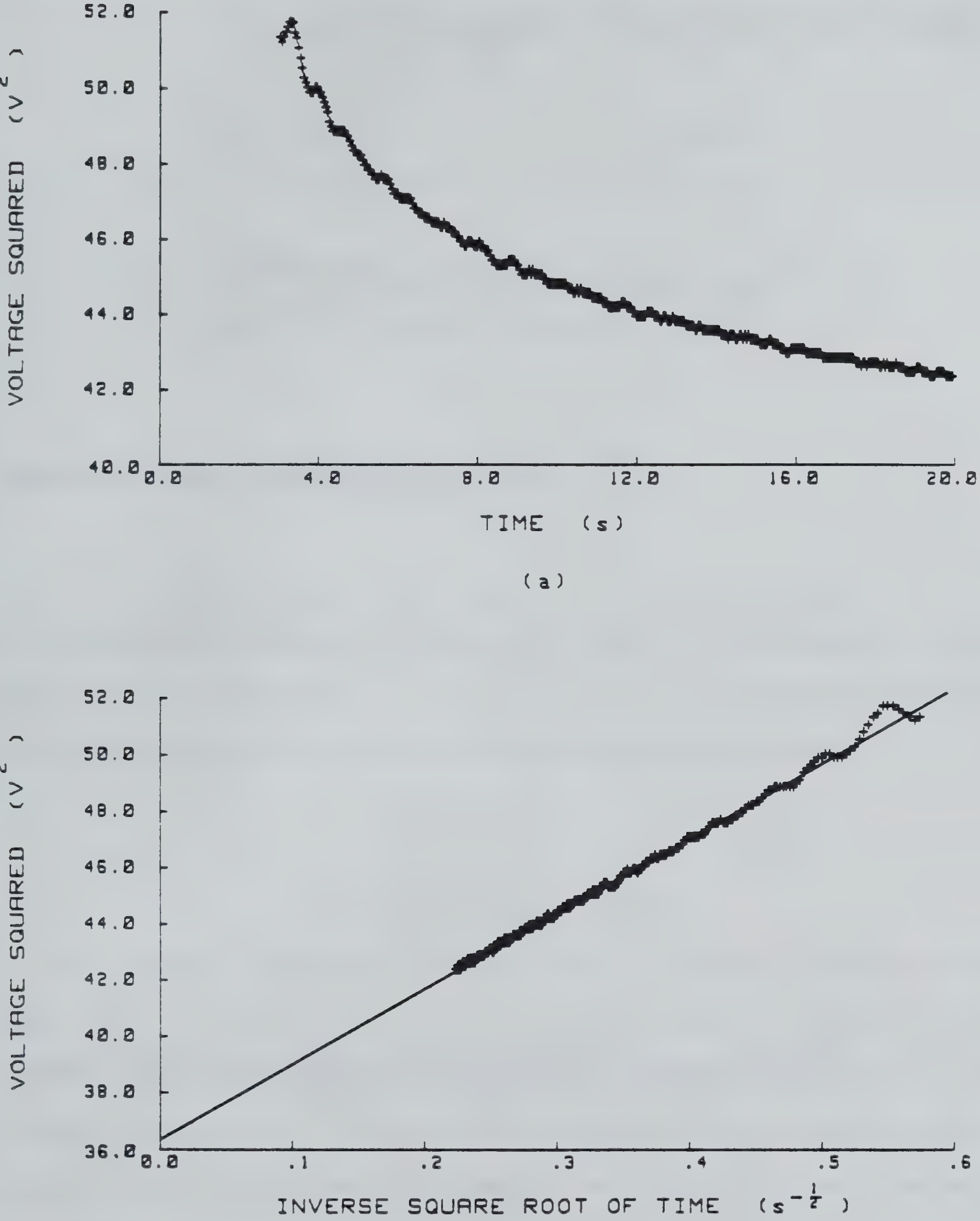
Following a simple change of variables ($\overline{T} = T - T_i$) , the two second order, partial differential equations (equations 1 and 2) and the four boundary conditions are transformed into the LaPlace domain. The resulting second-order, ordinary differential equations are solved, and the associated boundary conditions are applied. While in the LaPlace domain, the expression for the temperature distribution of both the bead and the medium are written such that steady-state (Γ) and transient (β) constants are separated. The inversion of these expressions to the time domain requires contour integration. The portion of the expressions dependent upon the steady-state constant was first inverted by Goldenburg and Tranter [48]. The inversion of the expressions dependent upon the transient constant contribution is



(a)

(b)

Figure 3. Power Dissipation Characteristics of the Glass-encapsulated Thermistor when Approximating a Step Temperature Rise



(a)

(b)

Figure 4. Power Dissipation Characteristics of the Teflon-encapsulated Thermistor when Approximating a Step Temperature Rise

described by Balasubramaniam and Bowman [4]. The resulting temperature distribution equations for the thermistor and the surrounding medium are

$$\bar{T}_b(r,t) = \frac{a^2\Gamma}{k_b}\left\{ \frac{1}{3}\frac{k_b}{k_m} + \frac{1}{6}\left(1 - \frac{r_2}{a_2}\right)\right.$$

$$\left. - \frac{2ab}{\pi r}\int_0^\infty \frac{\exp(-y^2t/\gamma_b)(\sin y - y\cos y)\sin\left(\frac{ry}{a}\right)}{y^2[(c\sin y - y\cos y)^2 + b^2y^2\sin^2 y]}\,dy \right\}$$

$$+ \frac{2\beta a}{k_b}\sqrt{\frac{\alpha_b}{\pi}}\int_0^\infty \frac{\exp(-y^2t/\gamma_b)}{y_2}$$

$$\left\{ -1 + \frac{\frac{a}{r}\frac{k_m}{k_b}\left[y\cos y - c\sin y + by^2\sqrt{\frac{\alpha_b}{\alpha_m}}\sin y\right]\sin\left(\frac{ry}{a}\right)}{(c\sin y - y\cos y)^2 + b^2y^2\sin^2 y}\right\}dy \qquad (10)$$

$$\bar{T}_m(r,t) = \frac{a^3\Gamma}{rk_b}\left\{\frac{1}{3}\frac{k_b}{k_m} - \frac{2}{\pi}\right.$$

$$\left.\int_0^\infty \frac{\exp(-y^2t/\gamma_b)(\sin y - y\cos y)[by\sin y\cos\sigma y - (c\sin y - y\cos y)\sin\sigma y]}{y^3[(c\sin y - y\cos y)^2 + b^2y^2\sin^2 y]}\,dy\right\}$$

$$- \frac{2\beta a^2}{k_b r}\sqrt{\frac{\alpha_b}{\pi}}$$

$$\int_0^\infty \frac{\exp(-y^2t/\gamma_b)(\sin y - y\cos y)[by\sin y\sin\sigma y + (c\sin y - y\cos y)\cos\sigma y]}{y^2[(c\sin y - y\cos y)^2 + b^2y^2\sin^2 y]}\,dy \qquad (11)$$

where

$$b = \left(\frac{k_m}{k_b}\right)\sqrt{\frac{\alpha_b}{\alpha_m}}\ ,\ c = 1 - \frac{k_m}{k_b}\ ,$$

$$\gamma = \frac{a^2}{\alpha}\ ,\ \sigma = \left(\frac{r}{a} - 1\right)\sqrt{\frac{\alpha_b}{\alpha_m}}\ ,\ \text{and}$$

y is the variable of integration.

Thermal Conductivity Equation

Because of the negative exponentials, only the first three terms in equation 10 remain when a steady-state condition exists (ie., $t \rightarrow \infty$). The resulting steady-state temperature distribution within the thermistor bead as a function of radial position is given by

$$T_b(r) = T_i + \frac{a^2\Gamma}{k_b}\left\{\frac{1}{3}\frac{k_b}{k_m} + \frac{1}{6}\left(1 - \frac{r^2}{a^2}\right)\right\} \tag{12}$$

This theoretical temperature distribution must be related to the experimentally measured thermistor temperature, T_t. In practice, the temperature measured using the thermistor is an average value which corresponds to the least resistive path within the thermistor's ceramic bead. To correlate the analytically determined temperature with the measured temperature, equation 12 is averaged over the entire volume of the sphere. Mathematically,

$$T_{b,ss} = \frac{1}{(4/3)\pi a^3}\int_0^a T_b(r)\,4\pi r^2 dr = T_i + \frac{\Gamma a^2}{3\,k_b}\left[\frac{k_b}{k_m} + \frac{1}{5}\right] \tag{13}$$

or expressed as a volume-averaged temperature rise,

$$\Delta T = \frac{\Gamma a^2}{3\,k_b}\left[\frac{k_b}{k_m} + \frac{1}{5}\right] \tag{14}$$

where $\Delta T = \Delta T_b = \Delta T_t$. The constant Γ ($=\dot{q}_{ss}$) represents the steady-state heat generation per unit volume. The volume is that of a sphere with radius a. The heat generation equals the power (given by the voltage squared divided by resistance) required to maintain the step temperature change within the thermistor. Making the proper substitution for the steady-state constant, equation 14 is rearranged to express the reciprocal medium thermal conductivity as the dependent variable.

$$\frac{1}{k_m} = 4\pi a\,\frac{\Delta T R_{t,f}}{V_{ss}^2} - \frac{1}{5k_b} \tag{15}$$

Thus, a relatively simple algebraic equation for evaluating the thermal conductivity of a test medium results. The temperature change is an input variable while the steady-state voltage squared is determined by extrapolating the transient data of the measured voltage, squared. The two thermistor properties, a and k_b, are determined via calibration.

Experimental Apparatus and Test Development

The primary functions of the data acquisition and control system are to measure and regulate the temperature of the thermistor probe. The experimental system operates in two different modes. One mode of operation is conventional temperature measurement where the heating of the thermistor by the signal current is negligible. In the other mode, the thermistor is deliberately heated to a controlled temperature a few degrees above that of the test sample. The equipment and procedures for these two tasks are described in this section.

Thermistor Probes

A glass-encapsulated and a teflon-encapsulated thermistor were evaluated for measuring thermal conductivity. The glass-encapsulated thermistor was a Fenwal GB32P8 standard glass probe with a nominal diameter of 2.54 mm and resistance rating of 2000 Ω at 25°C. The teflon-encapsulated thermistor was a YSI 44105 precision thermistor with a nominal diameter of 2.80 mm and resistance rating of 3000 Ω at 25°C. Although the active bead for the teflon-encapsulated thermistor is larger, both thermistor beads resemble prolate spheroids as shown in Fig. 5. The encapsulations are significantly different. The glass encapsulation is thinner and more closely approaches the desired geometry of a sphere while the teflon encapsulation resembles a cylinder with a "squared-off" end. Heat shrink tubing was used to seal the leads against moisture by effectively extending the encapsulations. To better seal the shrink tubing to the glass-encapsulated thermistor, an insulating varnish was first tried. Because the varnish deteriorated, however, a fine-thread was later wound at the section where the shrink tubing over-lapped the glass stem. A third thermistor was used for preliminary thermal conductivity tests and is briefly referred to later. With the exception of its resistance rating (1000 Ω at 25 °C), this third probe was exactly like the above described teflon-encapsulated thermistor. Unless otherwise specified, any reference to a teflon-encapsulated thermistor regards the nominal 3000 Ω probe. When a reference is made concerning "two" thermistors, the 2000 Ω glass- and 3000 Ω teflon-encapsulated thermistors are involved.

Rather than rely on the manufacturer's data, the resistance vs temperature characteristics of the two encapsulated thermistors were experimentally determined. A Fluke Platinum RTD acted as the temperature standard. The measurement uncertainty of the RTD is estimated to be less than ±0.03° C. The Fluke instrument has a digital display resolution of 0.01°C and an associated stability of ±0.01°C. Resistance was measured using the identical hardware as was employed in the thermal conductivity test. Using a constant temperature water bath, the probes were calibrated from 18°C to 30°C using approximately 1 °C increments. The two encapsulated thermistors were calibrated twice -- approximately four months apart -- to give an indication of probe stability.

A plot of temperature vs resistance for the glass-encapsulated probe is given in Fig. 6(a). The inverse relationship and the relatively high sensitivity are typical thermistor characteristics [49]. Three different functions, including the Steinhart-Hart equation [50], yielded curve fits with essentially equal closeness. The fit with the simplest form,

$$T = B + D \ln(R) \tag{16}$$

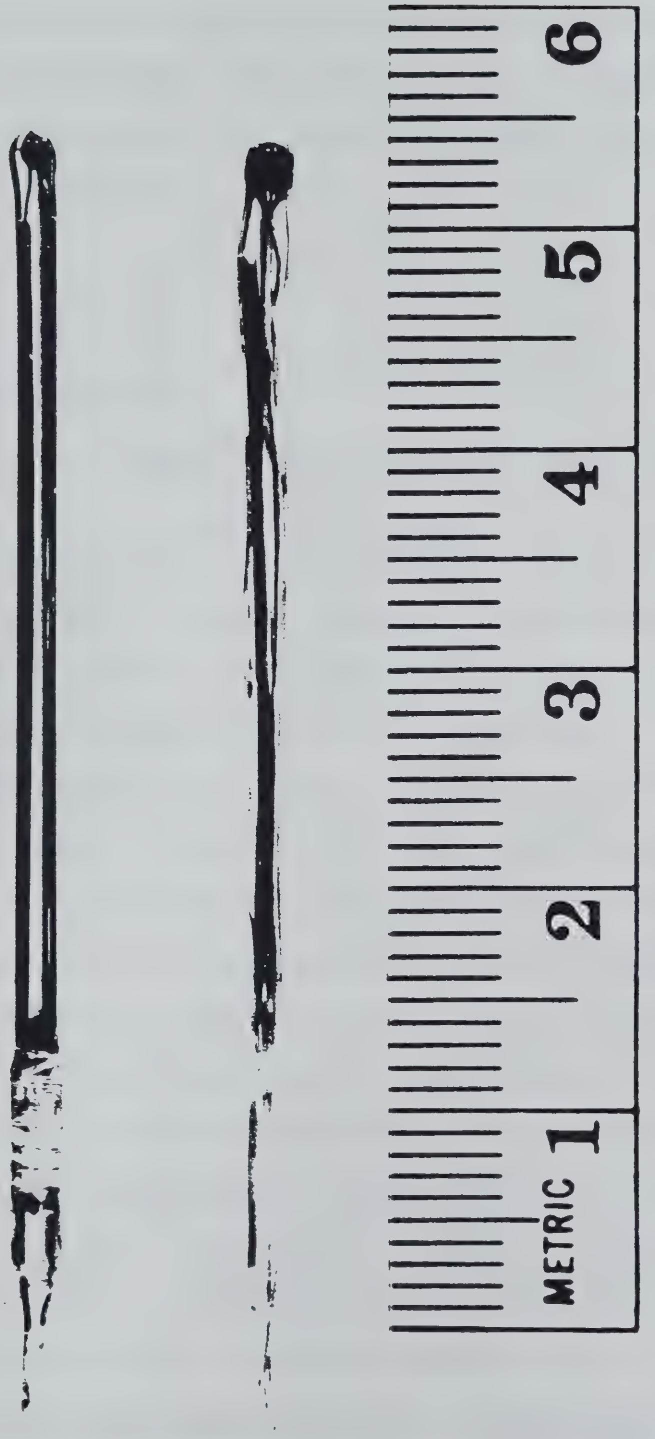


Figure 5. Thermistor Probes: Glass-encapsulated (top) and Teflon-encapsulated

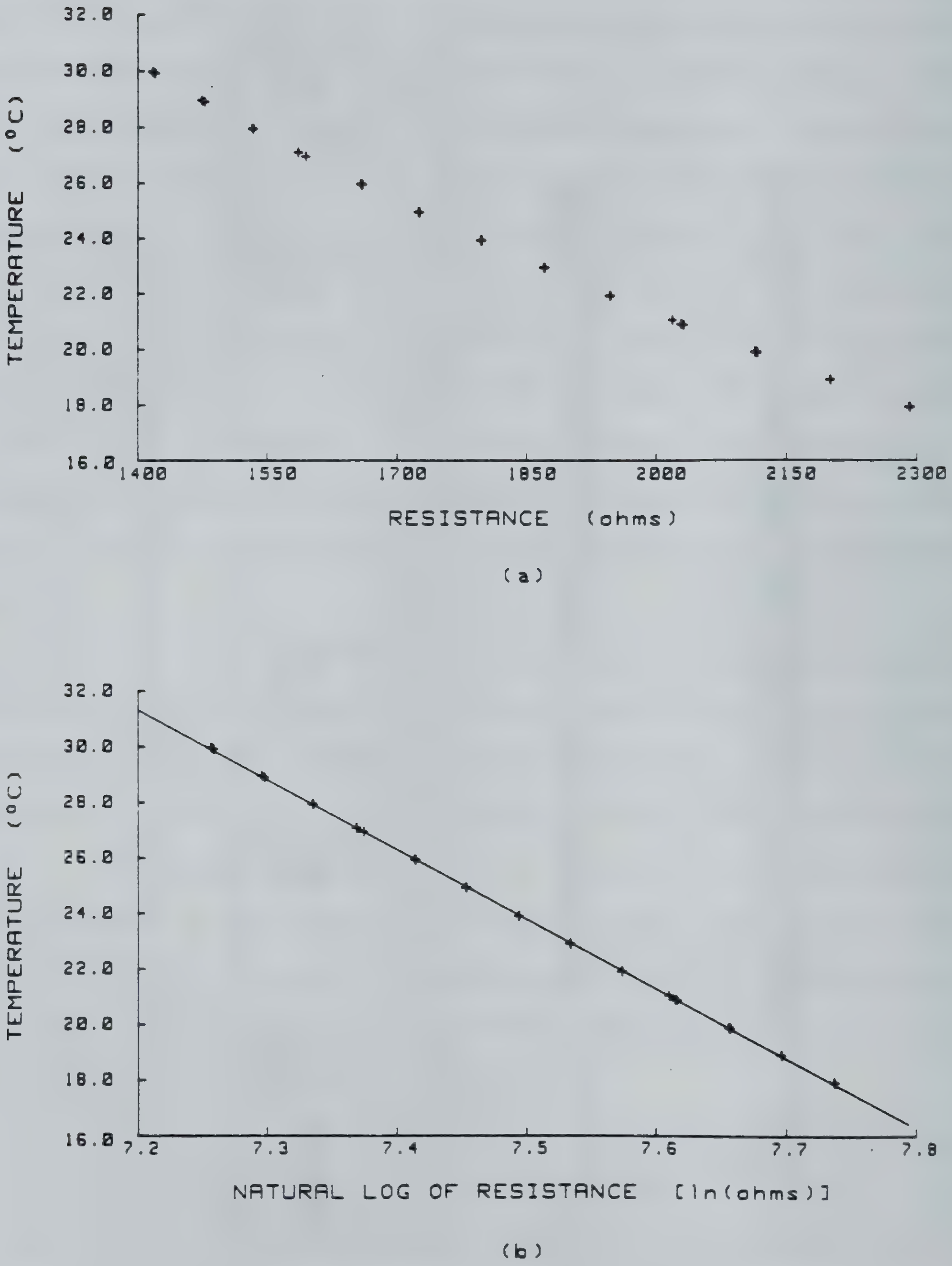


Figure 6. Thermistor Characteristics: (a) Temperature Versus Resistance (b) Curve Fit for Temperature Measurements

was actually used. Figure 6(b) shows a typical result when the thermistor temperature versus resistance data is fitted using equation 16. The constants were evaluated using the method of least squares [51]. The standard error for both probe curve fits is estimated to be less than ± 0.04°C. From a comparison of the curve fits from the data sets collected four months apart, the repeatability was ± 0.01 °C for the teflon-encapsulated thermistor and ± 0.03 °C for the glass-encapsulated thermistor.

System Hardware

The data acquisition and control system is more readily described once the two mode operation of a thermistor probe is understood. The configuration of the experimental apparatus and the development of the programming logic for the thermal conductivity test was aided by a related investigation by Fanney and Dougherty [52].

A thermal conductivity test begins by embedding the probe into an isothermal test sample. Enough time is allotted to insure that the probe-sample system achieves thermal equilibrium. Shortly before the actual transient measurements begin, the thermistor is used to measure the temperature of the sample. From this ambient temperature measurement and the specified temperature rise (either 2 or 3°C), the computer calculates the target thermistor temperature. The temperature of the probe is quickly elevated to this target value by resistive heating within the ceramic thermistor bead. The desired thermistor step temperature response is approached by using digital feedback in the form of an integral controller. The controlled variable is the current supplied to the probe. The thermistor voltage drop, the output current, and the resulting thermistor resistance are recorded as functions of time. The test run is terminated after a preset time, usually 30 seconds. The computer with the appropriate statistical software is subsequently used to reduce the large amount of data collected.

Two different methods were used to achieve an initially isothermal test sample. The liquid samples and the powdered sulfur, which were contained in 125 ml glass bottles, were submerged in a Thermomix constant temperature water bath. For the insulating materials, a constant temperature chamber was used. A Dynatech R-MATIC heat flow meter thermal conductivity instrument doubled as the constant temperature chamber. As implied by the instrument's name, the R-MATIC is conventionally used for measuring the thermal conductivity of insulation materials. The R-MATIC (which was used to give reference thermal conductivity values for the insulation materials tested using the thermistor probe) operates in compliance with an ASTM standard [53]. This operation, in general, involves sandwiching an insulation sample between isothermal "cold" and "hot" plates. Thermal conductivity is deduced from knowledge of the plate temperatures, the heat flux acrossed the sample, and the width of the sample once a steady-state heat transfer condition exists. When used as a constant temperature chamber, the two isothermal plates of the R-MATIC were operated at the same temperature. For all of the tests, the same set temperature of 25°C was used.

The centerpiece of the experimental apparatus was a Hewlett-Packard 9836A Series 200 computer. As is implied by Fig. 7, the 9836A computer controlled the other hardware components, including the thermistor. Besides I/O control, the computer

(1) prompted the user for pertinent test parameters (eg., desired temperature rise, total run time, etc),
(2) executed the integral control logic,
(3) recorded the pertinent run variables as a function of time, and
(4) printed and stored to a magnetic disc the collected data.

The internal clock of the 9836A was used for the time measurements. The time measurements using the crystal controlled clock are accurate to one one-hundredth of a second [54].

The DAC Power Supply Programmer (HP 59501B) and the Precision Constant Current Source (HP 6186C) controlled the electrical current supplied to the thermistor. After executing the feedback logic, the computer sent a digital word representing the desired output current

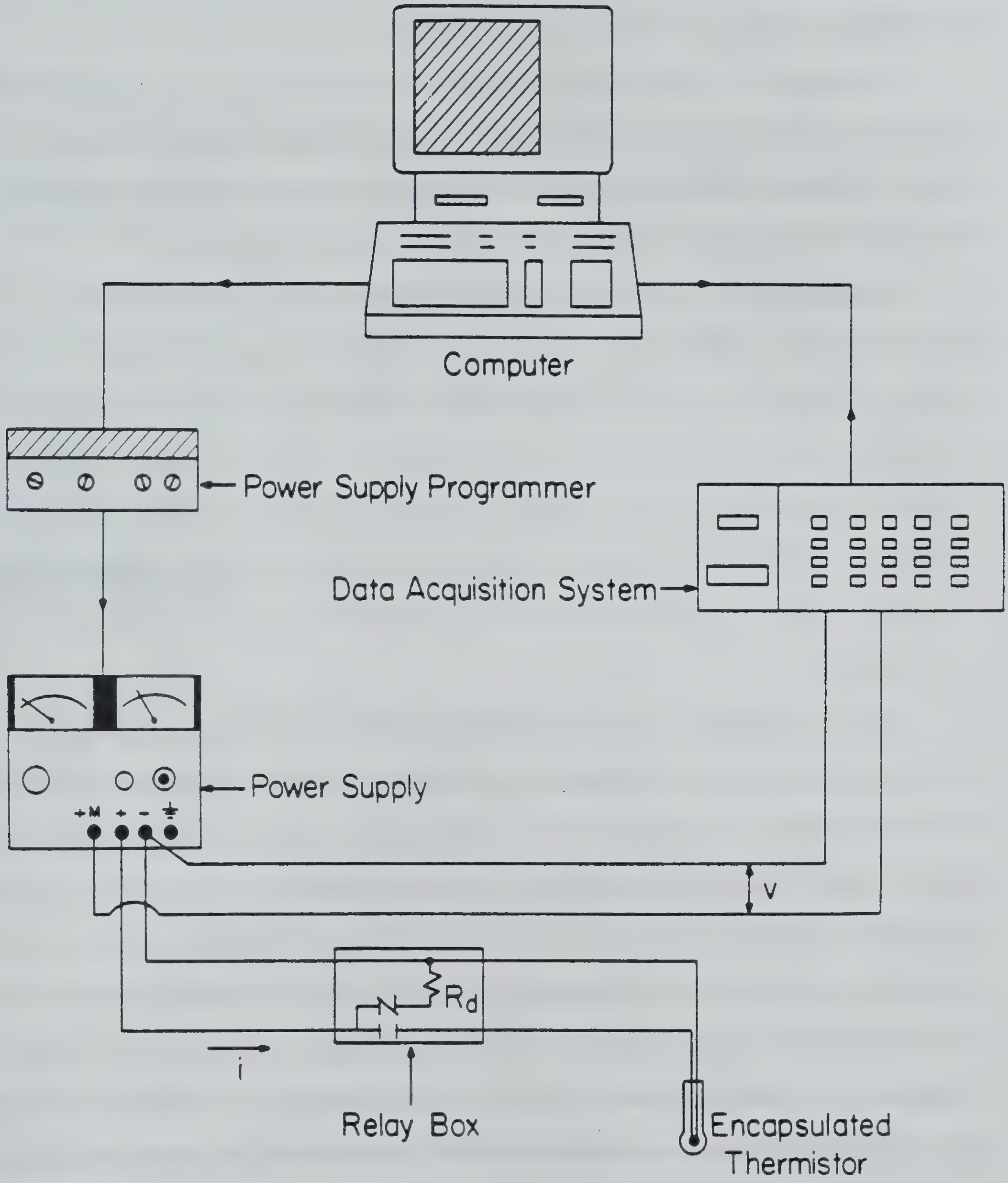


Figure 7. Configuration of Experimental Apparatus

to the HP 59501B. The HP 59501B converted this digital word into an analog voltage signal. The HP 6186C, which was physically hard-wired to the DAC Power Supply Programmer, sensed the change in this analog voltage and updated accordingly the dc current it supplied to the thermistor load.

At the start of a thermal conductivity test, the zero and full-scale current outputs from the remotely controlled power supply were set. A Hewlett-Packard Digital Multimeter (HP 3466A) was used as the amperage standard. The accuracy of the multimeter was checked against a lab standard and found to be within ± 2 μA over the range of operation.

When operated in the remote mode, the specified accuracy of the HP 6186C is ± 0.5 per cent of the output current [55]. Using the HP 3466A multimeter, the remotely operated HP 6186C power supply was tested for repeatability. In both this test and applications with the thermistor, the HP 6186C exhibited excellent precision, ± 1 μA. The resolution of the remotely controlled current source was limited by the digital-to-analog conversion performed by the HP 59501B. Specifically, the interval from zero to full-scale is evenly divided into 999 steps. For a typical test run, a full-scale current of 3.000 mA had an associated current output resolution of 3 μA.

The Hewlett-Packard Data Acquisition and Control Unit (HP 3497A) made both the initial thermistor resistance (ie., temperature) and transient voltage measurements. Resistance was measured using a 4-wire arrangement and a 10 μA signal current. This signal current caused negligible self-heating of the thermistor. For such resistance measurements, the resolution is 0.005 per cent of the reading, and the uncertainty is estimated to be less than ± 0.05 per cent of the reading [56]. The voltage measurements were made by the resident digital voltmeter (DVM) of the HP 3497A. The DVM incorporates a multislope A/D converter which integrates the voltage signal over time. Of the three options for the measurement resolution, the maximum, 5 1/2 digits, was used exclusively. The software-controlled voltmeter autozero function was disabled for the majority of the tests before initiating the transient voltage measurements. When the autozero function is enabled, the DVM better compensates for any internally generated offset errors but requires more time to make a measurement. The function was usually disabled because the offset error was believed to change minimally for the 30-second test and integration and 5 1/2 digits promote accuracy and resolution at the expense of the sampling rate. For cases where the autozero was enabled, the uncertainty of the transient voltage measurements is estimated to be less than ± 0.008 per cent of the reading [56].

The dummy resistor, housed in the relay box pictured in Fig. 7, provided a load for the HP 6186C power supply while it obtained its initial current setting (usually full-scale). Immediately before the transient voltage measurements began, the current supplied to the dummy resistor was switched to the thermistor. As a precautionary step, the dummy resistor replaced the thermistor as the external load on the power supply once the transient measurements terminated and the current output was zeroed.

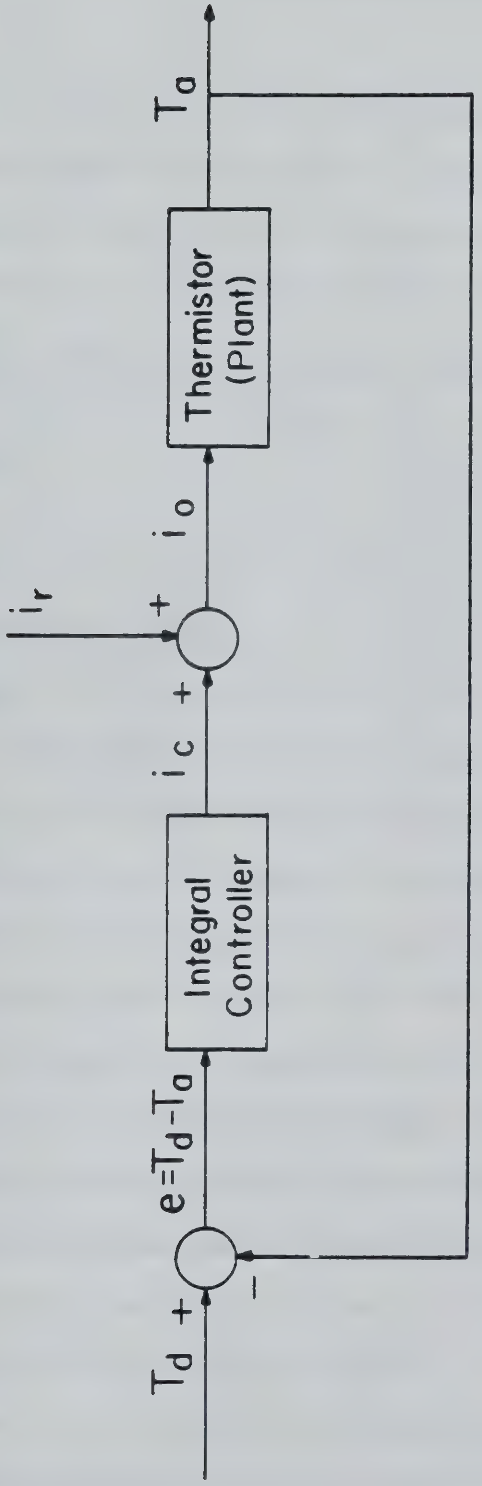
System Software

Software was developed to permit testing and to aid the data reduction sequence. The two main programs were the thermistor resistance vs temperature calibration and the thermal conductivity test programs. These programs were written in HP-compatible, IEM FORTRAN77. IEM FORTRAN77 code is compiled and executed within the Hewlett-Packard Pascal operating environment. A limitation of using the IEM FORTRAN77 for the two tasks is that the language lacks direct commands for I/O controlling of the data acquisition and control equipment. To overcome this I/O problem, the IEM FORTRAN77 programs called subroutines contained within a compiled HP Pascal program module. This HP Pascal program contained special I/O commands that are an integral part of the Hewlett-Packard Pascal language. Finally, a short program, written in HP BASIC, configured the test data before it was uploaded and analyzed using a copyrighted software package, the HP 98820A Statistical Library [51]. An IEM FORTRAN77 program that runs the thermistor-based thermal conductivity test, the Pascal program that permits the I/O, and the BASIC program that aids in the data reduction process are listed in the Appendix. The procedure for running these coupled programs accompanies the documented listings.

Integral Feedback

Integral feedback permitted controlling the temperature response of the thermistor such that a step change was approximated. The control was implemented using digital as opposed to analog technology. A block diagram of the feedback system along with the mathematical representation of the controller are pictured in Fig. 8. Although thermistor resistance was the experimental feedback variable, to aid clarity, temperature rather than resistance is used here to explain the feedback strategy. The difference between the desired elevated temperature, T_d , and the instantaneous thermistor temperature, T_a , yielded the error, *e*, which was integrated over time. While the error was driven to zero (ie., $T_d = T_a$), the integrated error approached a finite constant. The gain setting, K, scaled the integrated error to give a correction current, i_c , of a suitable, relative magnitude. The correction current was added to a reference current, i_r . For all the tests conducted during this investigation, the reference current was the full-scale current. The new current setting, i_o , was supplied to the thermistor load, a new thermistor temperature was measured, and the process repeated.

Two problems related to the actuator becoming saturated were overcome using programming logic. If the control logic yielded an updated current output that was greater than full-scale or that was negative, then the updated output was set to the appropriate boundary value. Secondly, a phenomenon known as integrator windup was avoided by temporarily disabling the error integration [57]. Continued integration during a saturation condition causes potentially large integrator build up. This build up translates into overshoots in the system response once the error that drove the actuator to saturation changes sign.



(a)

$$i_o = i_r + i_c \qquad \text{where} \qquad i_c = K\int_0^t e(t)\,dt$$

(b)

Figure 8. Feedback Control Strategy: (a) Block Diagram (b) Mathematical Representation

When the integration is interrupted, overshoots are minimized with the control variable (current, for this application) being reduced at the proper instant.

System Speed

System speed as used here is the frequency of measuring the thermistor's voltage and updating the current output. As shown below, system speed influenced the effectiveness of the integral controller and the amount of data collected during the short test interval.

An acceptable balance between maximizing system speed and measurement accuracy was achieved for the thermal conductivity measurement technique. During this investigation, system speed was improved from an initial value of slightly more than 4 Hz to a final value of 21.6 Hz. Measures taken to increase system speed included disabling the autozero function (15.6 Hz with autozero enabled) and making the thermistor voltage measurement at the lone external port of the HP 3497A's DVM as opposed to using a channel on a multiplexing card. The loss in speed resulting from using a multiplexer card channel is attributed to additional internal relay switching within the HP 3497A. After these changes, the main speed limitation was directly linked to the integrating A/D conversion performed by the HP 3497A DVM. For the 5 1/2 digit voltage measurements with the autozero function disabled, the maximum sampling rate, according to the manufacturer's literature, ranges from 27 to 50 Hz [56]. The lower bound appears to be more representative of the ceiling sampling rate for the thermistor application.

System Performance: Temperature Response

The extent to which the experimental system performance approached the theoretical probe operation was investigated by using the temperature response plots from thermal conductivity tests. The temperature response plot was the most available indicator of system performance. For example, the contact resistance between the probe and the surrounding medium (which should theoretically be zero) and the spatial distribution of the bead heat generation (which should ideally be uniform) are two other performance indicators that are comparatively more difficult to experimentally quantify. Thus, the development and refinement of the experimental apparatus concentrated on reducing the initial transients as the probe tries to approach a step temperature change. The theoretical step response can only be approximated because the thermistor has a finite even if small heat capacity and, in addition, the power supply has a finite current limit.

Once the basic measurement apparatus and software codes were streamlined to yield the fastest temperature response plots, four test parameters were investigated for their influence on system performance. These parameters were the system speed, the gain setting on the integral feedback, the power supply full-scale current setting, and the resistance rating of the thermistor.

The effect of system speed was initially investigated by comparing the results from a fast and a slow run. The system speed results, as shown in Fig. 9 are from a test with the nominal 3000 Ω teflon-encapsulated thermistor dissipating heat to a ethylene glycol medium. The thermistor completed the initial transient response in approximately seven seconds when the system speed was 15.6 Hz as shown in Fig. 9(a). Figure 9(b) shows that the faster system speed (21.6 Hz) requires approximately three seconds. Since the thermal conductivity equation (eqn. 15) is based on a temperature change that remains constant with time (and, ideally, should be a step), the data collected during the initial transients were not used when

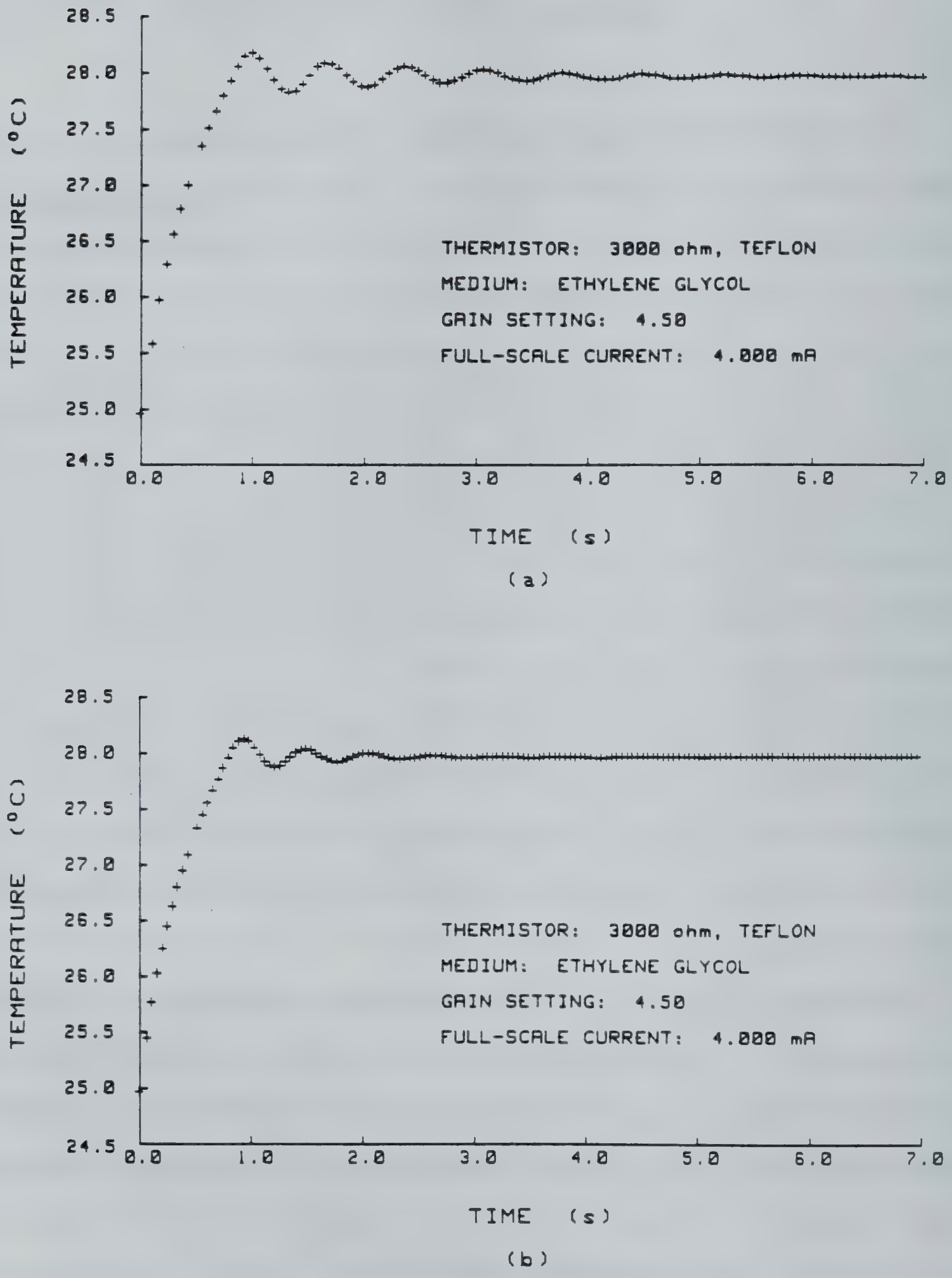


Figure 9. Effect of System Speed: (a) 15.6 Hz (b) 21.6 Hz

plotting the characteristic data of V^2 vs $t^{-1/2}$. The system speed is discussed further in connection with the thermal conductivity test results.

The gain setting and the power supply full-scale current had minimal influence on the temperature response time while the importance of the resistance rating was second to system speed. The gain setting and power supply full-scale current setting influenced the shape of the temperature vs time plot and, if either or both were made too large, the system became unstable. The condition of instability was experimentally observed. Specific values for the gain and full-scale current settings which yielded the unstable response were not rigorously studied because the condition was dependent upon the combination of many test variables (eg., the probe, the test medium, the system speed, etc.). The effects of gain setting and maximum current setting are exhibited in Figs. 10 and 11, respectively. For these plots, the nominal 1000 Ω, teflon-encapsulated thermistor dissipated heat to a glycerin medium. The system speed was 21.6 Hz. Referring to Fig. 10, the larger gain setting produced less overshoot than the lower setting but also yielded more fluctuations. Referring to Fig. 11, the larger full-scale current gave a faster temperature rise but caused greater overshoots of the desired elevated temperature as compared to the smaller current setting. In both cases, there was no discernible effect on the settling time. Comparing the four graphs, all the transient temperature responses end at approximately five seconds. Since the gain and current settings had little effect on the time required to complete the transients, a last comparison was made between the two teflon-encapsulated thermistors. For a system speed of 21.6 Hz and a surrounding medium of glycerin, the nominal 3000 Ω thermistor, as shown in Fig. 12, completed its transient response in approximately three seconds as compared to five seconds for the nominal 1000 Ω thermistor. This last result led to the selection of the nominal 3000 Ω thermistor as the teflon-encapsulated probe used for the remainder of the study.

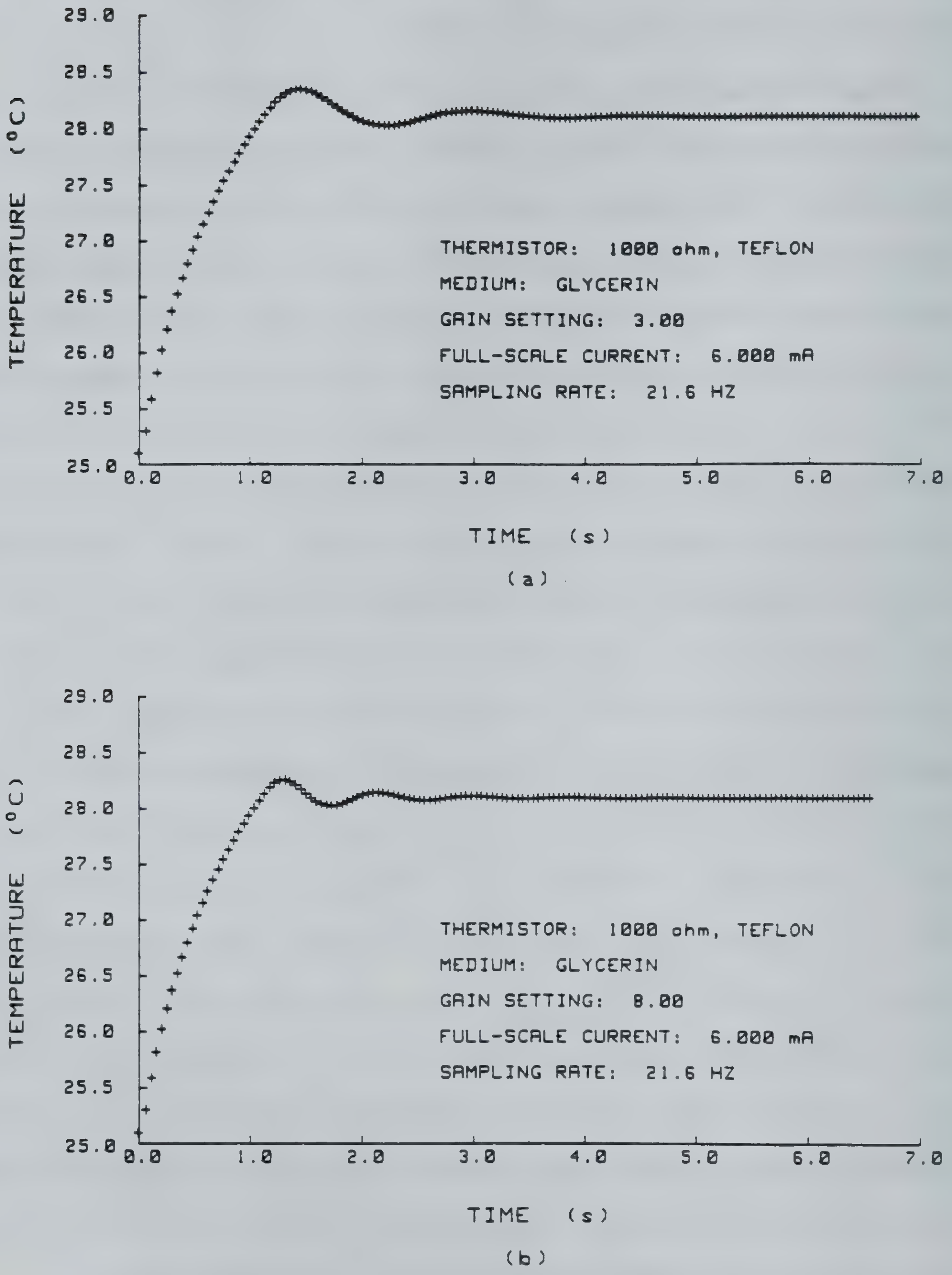


Figure 10. Effect of Gain Setting: (a) Lower Setting (b) Higher Setting

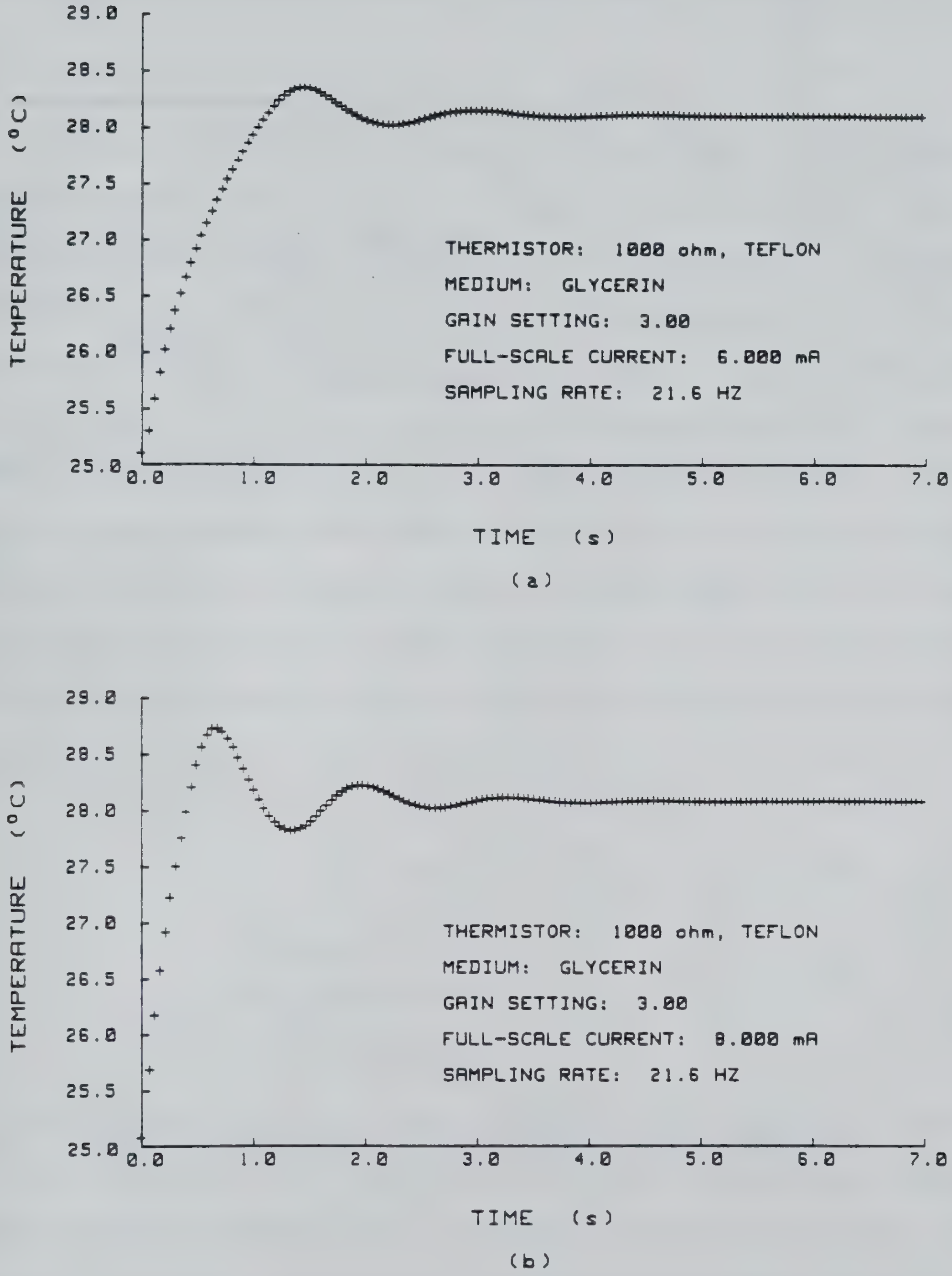


Figure 11. Effect of Full-scale Current Setting: (a) Lower Setting (b) Higher Setting

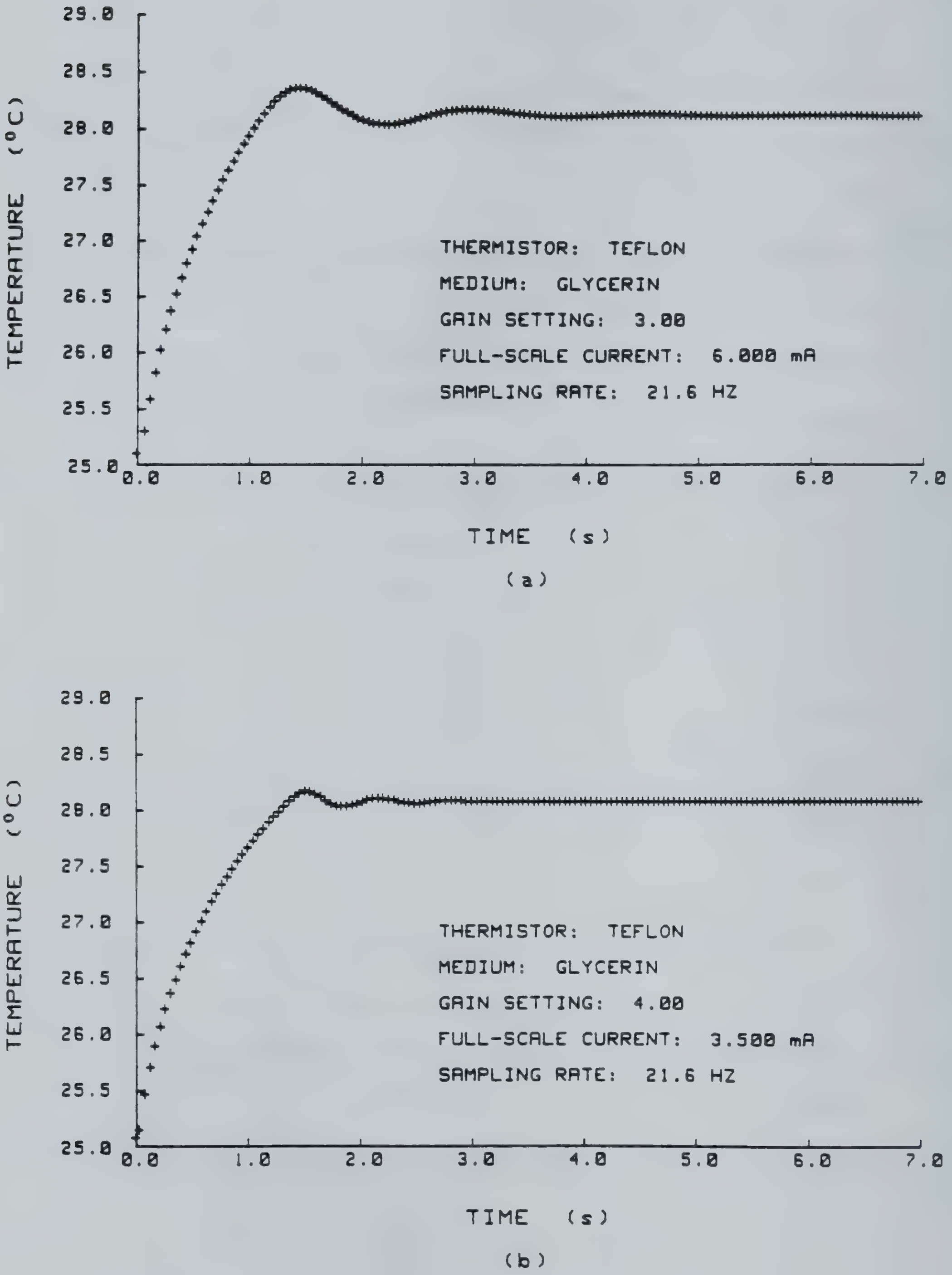


Figure 12. Effect of Thermistor Resistance Rating: (a) Nominal 1000 ohm (b) Nominal 3000 ohm

Calibration and Application: A General Overview

The probe thermal conductivity calibration test is actually the same as the previously described measurement test. For calibration, however, equation 15 (repeated below) is rearranged as shown by equation 17 where C and k_m are known quantities. The two unknowns in equation 17, a and k_b, are deduced from a plot of the resulting linear equations for each calibration medium. Three calibration media were used with the exception of one probe calibration which used two materials. Ideally, the three calibration lines (equation 17) should intersect at a point, thus indicating that two rather than three calibration media would have sufficed. In practice, however, the intersection of these three lines forms a triangle with its centroid being taken as the best approximation of the probe's effective properties. Such a calibration plot accompanies the presentation of the measurement results for each probe in the next chapter. Once these effective properties are known, the application of equation 15 is straight forward with k_m as the only unknown parameter.

$$\frac{1}{k_m} = 4\pi a \, \frac{\Delta TR_{t,f}}{V_{ss}^2} - \frac{1}{5k_b} \qquad (15)$$

$$\frac{1}{k_b} = 5Ca - \frac{5}{k_m}; \quad \text{where } C = 4\pi \, \frac{\Delta TR_{t,f}}{V_{ss}^2} \qquad (17)$$

Once calibrated, each probe was used to measure the thermal conductivity of a group of materials. The results from the measurements were used to evaluate and, to a lesser degree, to validate the thermistor-based measurement technique. Understandably, probe evaluations were aided by comparing thermal conductivity values between those measured using the thermistor-based technique and a second, established method. Observed trends for both the glass- and teflon-encapsulated thermistors, however, provided equal insight.

For the probe evaluations as well as the calibration tests, materials with known k-values were used. The calibration materials, in addition, bracketed the thermal conductivity interval of eventual probe application [1]. Documented sources provided the reference thermal conductivity data for the liquids. For the insulation materials tested, an R-MATIC heat flow meter thermal conductivity instrument was used to yield reference values.

By the time the thermal conductivity measurements documented in next chapter were conducted, the experimental apparatus and measurement procedure had been completely refined. Testing was reduced to repeating a standard procedure. For example, a typical thermal conductivity measurement lasted 30 seconds. The follow-up data reductions, from which a value of thermal conductivity resulted, required less than 15 minutes. Results and discussion concerning performance capabilities of the two thermistors are detailed in the next chapter.

Results and Discussion

The overall results gave both a basis to evaluate the general measurement technique and the two probe types. The digital implementation of the control technique was successful. With some restrictions, the use of the relatively large, encapsulated thermistors was also validated. For the two probe types, the results were surprisingly different. The glass-encapsulated thermistor yielded better results when used on liquids while the teflon-encapsulated probe worked better on insulation materials.

For a given test medium, multiple runs were conducted. Of the significant test variables, the status of the autozero function and the magnitude of the desired temperature rise were most often changed from run to run. A temperature rise of either 2 or 3 °C was used. The autozero function was usually enabled for one of the multiple runs. The standard run time was 30 seconds.

Glass-encapsulated Thermistor

The glass-encapsulated thermistor was used to measure the thermal conductivities of fifteen liquids. The thermal conductivities of these liquids ranged from 0.6 (distilled water) down to 0.1 W/m-°C (tert butanol). Using aqueous ethylene glycol solutions, the glass-encapsulated probe was also tested as an interpolating instrument. The designation "interpolating instrument" signifies calibrating the thermistor using two reference materials which bracket the range of application. The calibrated probe is then used only on materials having compositions similar to the calibration media and thermal conductivities which fall within the bracket. The probe interpolates between the high and the low reference values for such applications. The probe was not used to measure the thermal conductivity of insulation materials for reasons discussed later.

Probe Calibration

For the glass-encapsulated thermistor, the three calibration media used were distilled water, glycerin, and toluene. Distilled water and toluene bracket, while glycerin divides, the specified thermal conductivity measurement interval. For all three materials, reliable sources exist which document the thermal conductivities at 25°C. The thermal conductivity test was repeated four times for each medium.

Probe calibration centers on the results of two plots. From the collected data, a plot of V^2 vs $t^{-1/2}$ is developed and correlated with a straight line. Figure 13 shows a representative plot for all three of the mediums used to calibrate the glass-encapsulated thermistor. The y-intercept of the fitted data corresponds to the steady-state voltage squared, V_{ss}^2. Substituting for the known quantities in equation 17, a linear expression for the reciprocal bead thermal conductivity, $1/k_b$, as a function of the probe radius, a, results. Since four calibration tests

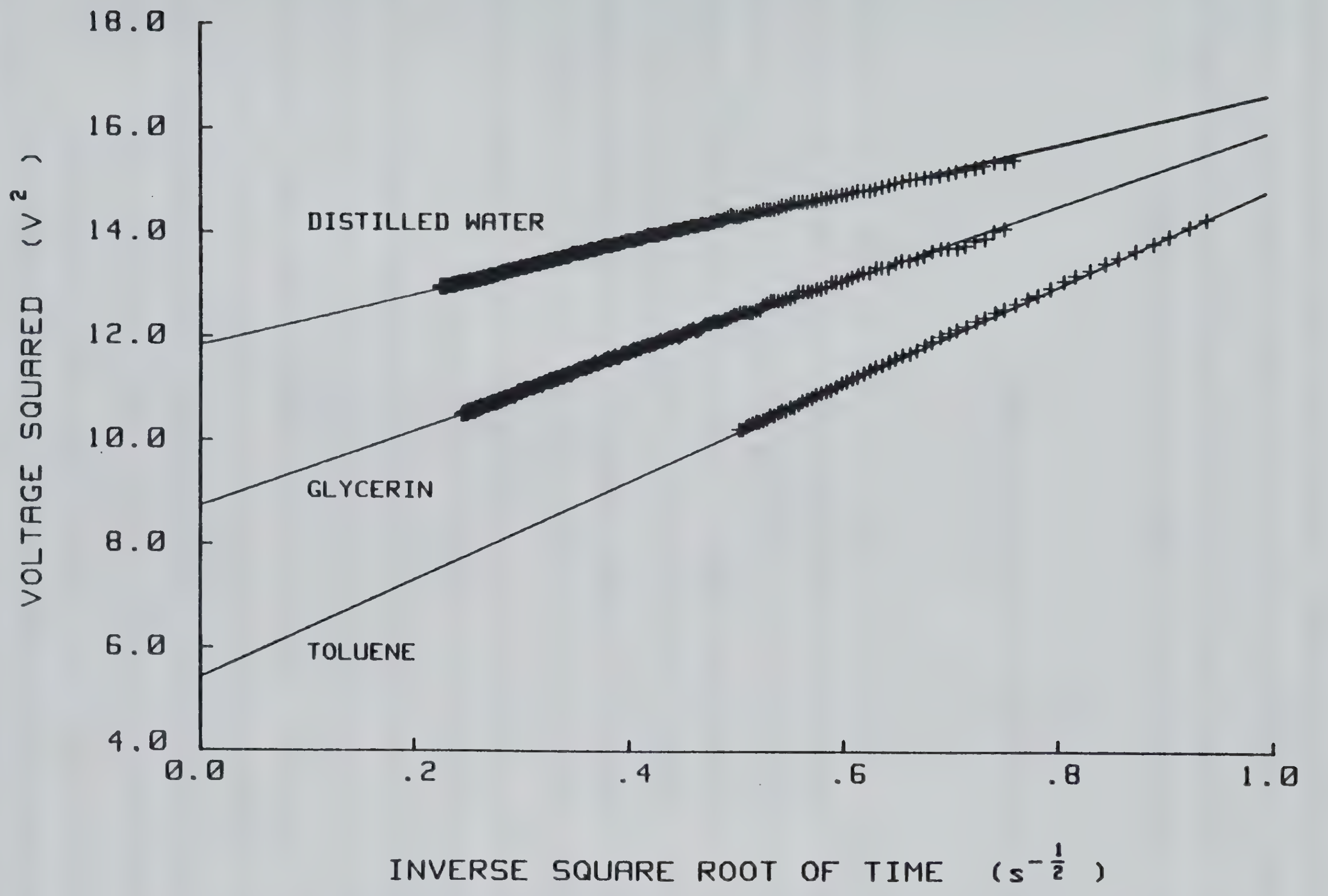


Figure 13. Glass-encapsulated Thermistor Calibration Materials: Characteristic Curves

were conducted on each medium, four different equations resulted. The corresponding four values for C (defined with equation 17) were averaged to give a single calibration curve for each medium. The calibration curves for the three media are plotted in Fig. 14. From the centroid of the resulting triangle, the probe effective radius and the reciprocal bead thermal conductivity were determined to be 1.52 mm and 17.6 m-°C/W, respectively.

Probe Thermal Conductivity Measurements

The thermal conductivity values and related test data were used to qualify probe performance. For the glass-encapsulated thermistor, multiple tests were conducted using powdered sulfur and 12 other liquids besides the three calibration media. A representative sample of the test data is given in Table 1. Given that an R^2 upper bound of 1 represents a perfect fit, the very high R^2 values from the V^2 vs $t^{-1/2}$ plots indicate that the data sets closely approximated straight lines. All of the fits corresponded to R^2 values of 0.997 or higher. For the liquids tested, the value of C (equation 17) was both repeatable and independent of the magnitude of the temperature change. For example, the C values for identical tests with 50 per cent aqueous ethylene glycol, table entries 13 and 14, differ by less than 0.7 per cent. For the same material, the C values for a 2°C and a 3°C rise are nearly identical, 19501 vs 19532. The results for the powdered sulfur were comparatively poor as is evident by the scatter of its C values. As compared to the liquids, tests on powdered sulfur yielded relatively low V_{ss}^2 values. The slower sampling rate and more accurate measurement associated with an enabled autozero function did not influence the V_{ss}^2 values in any consistent manner. Identical tests on glycerin (6 and 7) and toluene (10 and 11) show slightly lower values for V_{ss}^2 for the disabled condition whereas tests on acetone (2 and 3) show an opposite effect.

The influence of system speed was further investigated by varying the sampling rate while testing the glass-encapsulated thermistor in glycerin. The lowest sampling rate, 2.86 Hz, required approximately eight seconds to complete its initial transients. Therefore, in an

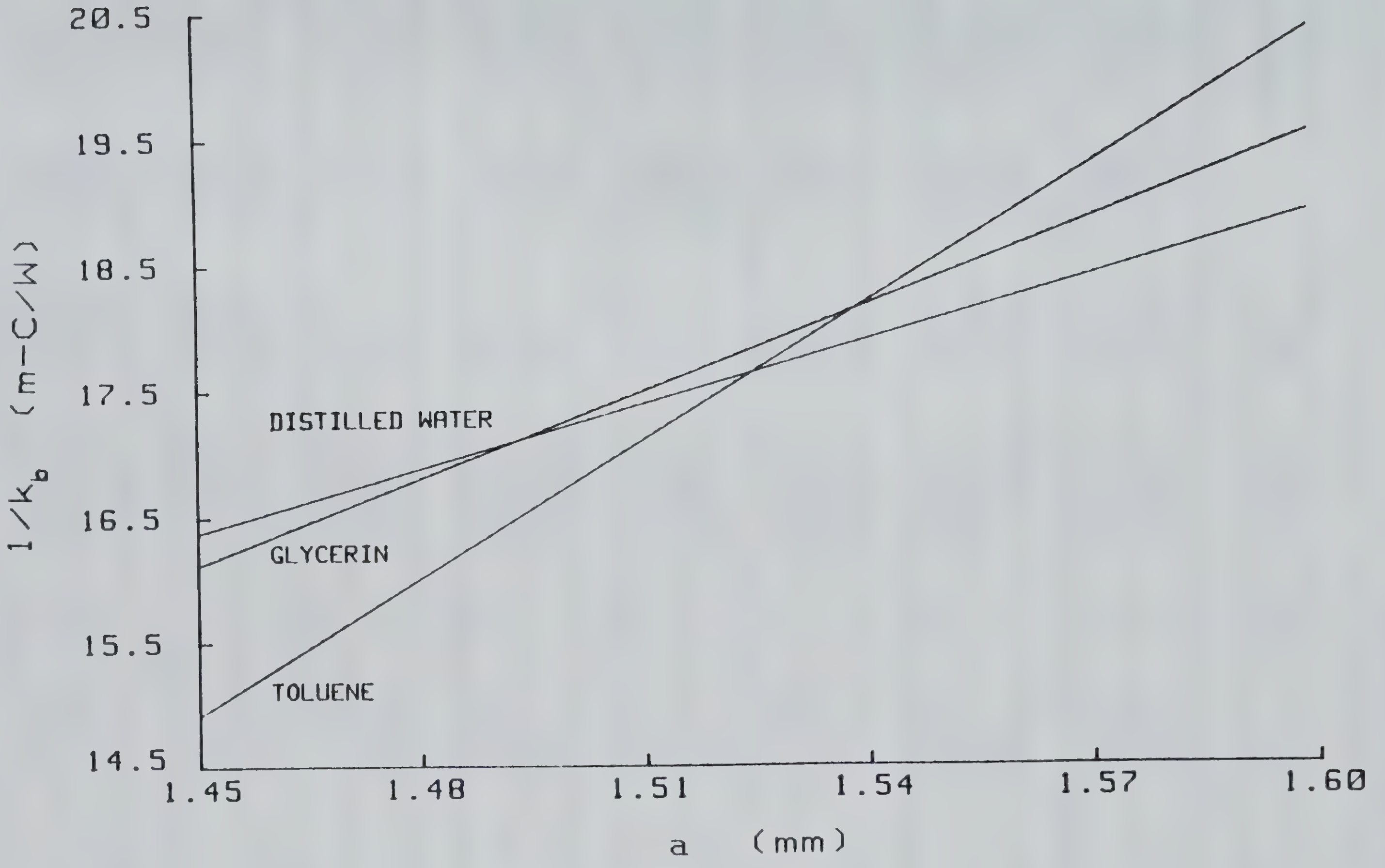


Figure 14. Determination of the Glass-encapsulated Thermistor Effective Properties

Table 1. Glass-encapsulated Thermistor Test Data

I.D. No.	Medium	T_i (°C)	ΔT (°C)	Autozero Function	V_{ss}^2 (V^2)	R^2	C (°C/W)
1	acetone	24.95	3	Disabled	9.4696	0.9971	30478
2		24.96	2	Disabled	6.4476	0.9988	31040
3		24.96	2	Enabled	6.5052	0.9983	30763
4		24.96	2	Disabled	6.4332	0.9991	31117
5	glycerin	25.07	2	Disabled	8.7320	0.9979	22820
6		25.08	2	Disabled	8.7344	0.9978	22806
7		25.08	2	Enabled	8.6952	0.9982	22906
8		25.09	3	Disabled	12.388	0.9982	23168
9	toluene	25.07	3	Disabled	8.0555	0.9992	35657
10		25.08	2	Disabled	5.4022	0.9997	36873
11		25.08	2	Enabled	5.3571	0.9996	37186
12		25.07	2	Disabled	5.4386	0.9995	36637
13	50 per cent ethylene glycol (by mass)	25.02	3	Disabled	14.762	0.9992	19501
14		25.02	3	Disabled	14.850	0.9990	19379
15		25.01	2	Disabled	10.275	0.9985	19411
16		25.02	2	Disabled	10.222	0.9978	19532
17	n-heptane	25.08	2	Disabled	4.9435	0.9997	40292
18		25.10	3	Disabled	7.2069	09995	39808
19		25.10	3	Disabled	7.2144	0.9990	39770
20		25.10	2	Disabled	5.0947	0.9995	39076
21	powdered sulfur	24.95	3	Disabled	1.5892	0.9994	181,640
22		24.99	2	Disabled	0.8149	0.9994	245.280
23		25.00	2	Enabled	0.7853	0.9989	245,510
24		25.01	2	Disabled	1.0088	0.9994	197,980
25	methanol	25.12	2	Disabled	8.3417	0.9996	23845
26		25.12	2	Enabled	8.3059	0.9995	23947
27		25.12	3	Disabled	11.934	0.9992	24018
28		25.12	3	Disabled	11.959	0.9991	23972
29	castor oil	25.07	2	Disabled	6.7400	0.9992	29566
30		25.08	2	Enabled	6.6856	0.9988	29791
31		25.09	3	Disabled	9.5502	0.9994	30058
32		25.09	2	Disabled	6.7326	0.9993	29575

effort to better compare characteristic plots and ultimately V_{ss}^2 values, the curve fits for each sampling rate tested were determined from the data collected after 8 seconds had elapsed. Because the initial temperature was nearly identical for each test (25.03°C) and a 2°C temperature rise was always used, determining the effect of system speed was reduced to comparing V_{ss}^2 values. As was observed in Fig. 9, a higher sampling rate yields a temperature response more closely approximating the theoretical step change. Despite this dependency, the results given in Table 2 show that the V_{ss}^2 values were not systematically affected by the sampling rate. Assuming the trend depicted in Table 2 continues to hold for sampling rates greater than 21.6 Hz, attaining a step temperature change is not as critical as originally believed. As is shown later, however, a fast system speed is important for other reasons.

The thermal conductivities of the materials measured using the glass-encapsulated thermistor are listed along with those of a second documented source in Table 3. The calibration materials, designated by asterisks, are included to quantify the influence of having the calibration curves form a triangle as opposed to intersecting at a point. The magnitude of the largest per cent difference for these calibration and application materials is 0.7. This result suggests that the relative size of the calibration triangle effectively approximates a point. For ten of the other twelve liquids, the measurements made using the thermistor differed by less than 8 per cent when compared to reference values. The measured thermal conductivities for the aqueous ethylene glycol solutions, especially for the 50 per cent solution, were in good agreement with the reference values. The lack of agreement between the measured and reference values for methanol, was unexpected. The test data for methanol was comparable to data of other liquids and, in fact, the precision of its *C* values were the best of any material tested, ie. the per cent difference between the high and low *C* values was 0.7. The reason for this deviation remains unexplained. The measured thermal conductivity of powdered sulfur is not expected to be representative of the the true value. This belief is based on the significant random scatter observed in the values of *C* for the four test runs. A reference k-value for powdered sulfur was never identified. Reference 41 lists the thermal conductivity of solid sulfur which is 0.21 or 0.27 W/m-°C (depending on its structure,

Table 2. Steady-state Voltage Squared Values as a Function of the Sampling Rate

Sampling Rate (Hz)	V_{ss}^2 (V^2)
2.86	8.4908
4.80	8.5264
6.21	8.5766
8.14	8.4986
11.81	8.5361
17.88	8.5046
19.56	8.5663
21.58	8.53109

Probe: Glass-encapsulated Thermistor

Medium: Glycerin

Maximum Current: 2.700 mA

Limits on the Reduced Data: $8s < t < 30s$

Table 3. Glass-encapsulated Thermistor Thermal Conductivity Measurement Results

Medium	Thermal Conductivity (W/m • °C) Thermistor k_t	Reference k_r	Reference No.	Per cent** Difference
castor oil	0.181	0.180	11	-0.6
glycerin*	0.290	0.292	30,36	0.7
toluene*	0.132	0.1311	35	-0.7
n-heptane	0.117	0.1228	35	4.7
ethyl alcohol	0.192	0.168	36	-14.3
methanol	0.266	0.199	36	-33.7
powdered sulfur	0.0158	--	--	--
distilled water*	0.611	0.6067	35	-0.7
acetone	0.171	0.159	36	-7.5
ethylene glycol	0.258	0.257/0.28	11/43	-0.4/7.1
tert butanol	0.122	0.119	30	-2.5
20 per cent (by mass) ethylene glycol	0.532	0.520	43	-2.3
40 per cent ethylene glycol	0.447	0.448	43	0.2
50 per cent ethylene glycol	0.418	0.418	43	0
60 per cent ethylene glycol	0.376	0.39	43	2.6
80 percent ethylene glycol	0.312	0.33	43	6.1

*designates calibration material

**Per Cent Diff. $= \dfrac{(k_r - k_t)}{k_r} \times 100$

amorphous or polycrystalline). The observed discrepancies for methanol and powdered sulfur support validating a calibrated probe on as many of the applied materials as possible.

As part of an idea which evolved from experience and was further influenced by Woodbury [1], the probe-based technique was evaluated for making interpolating measurements. Interpolating means here that the probe would only be used on materials having compositions and thermal conductivities similar to those of the calibration media, as in the case of aqueous solutions or, possibly, insulation materials. Two calibration media would be used and their thermal conductivities would set the extreme limits of application. The calibration procedure is simplified to plotting only two calibration expressions (or equivalently, simultaneously solving two equations with two unknowns).

The glass-encapsulated thermistor performed well as an interpolating instrument. Using 100 per cent ethylene glycol and distilled water as the calibration media, the probe effective radius and reciprocal thermal conductivity measurement gave 1.31 mm and 13.92 m-°C/W. Given these effective probe properties, the thermal conductivities of five different aqueous ethylene glycol solutions were determined. The measured results as shown in Table 4 agree well with the reference values. The measured thermal conductivities for 60 and 80 per cent solutions were in complete agreement. Figure 15 shows a curve fitted to the reference values and the data points from the thermistor probe measurements. Reference 43 was used exclusively for reference *k*-values of all seven materials. As discussed earlier, significant discrepancies exist among the reported values for the thermal conductivity of ethylene glycol. The accuracy of the values reported by reference 43 are used even though similar discrepancies are likely for the aqueous solutions. Ethylene glycol solutions were used because they have similar compositions and thermal conductivities that span a relatively wide range (0.25 to 0.6 W/m-°C). Finally, the effective properties from this second calibration differ from those of the first (1.31 mm vs 1.52 mm and 13.95 m-°C/W vs 18.16 m-°C/W), thus exhibiting the influence of the selected calibration materials on the probe parameters.

Table 4. Probe Application as an Interpolating Instrument

Medium	Thermal Conductivity (W/m • °C) Thermistor	Reference	Per cent Difference
20 per cent (by mass) ethylene glycol	0.534	0.520	-2.7
40 per cent ethylene glycol	0.459	0.448	-3.5
50 per cent ethylene glycol	0.432	0.418	-3.3
60 per cent ethylene glycol	0.393	0.39	0
80 per cent ethylene glycol	0.332	0.33	0

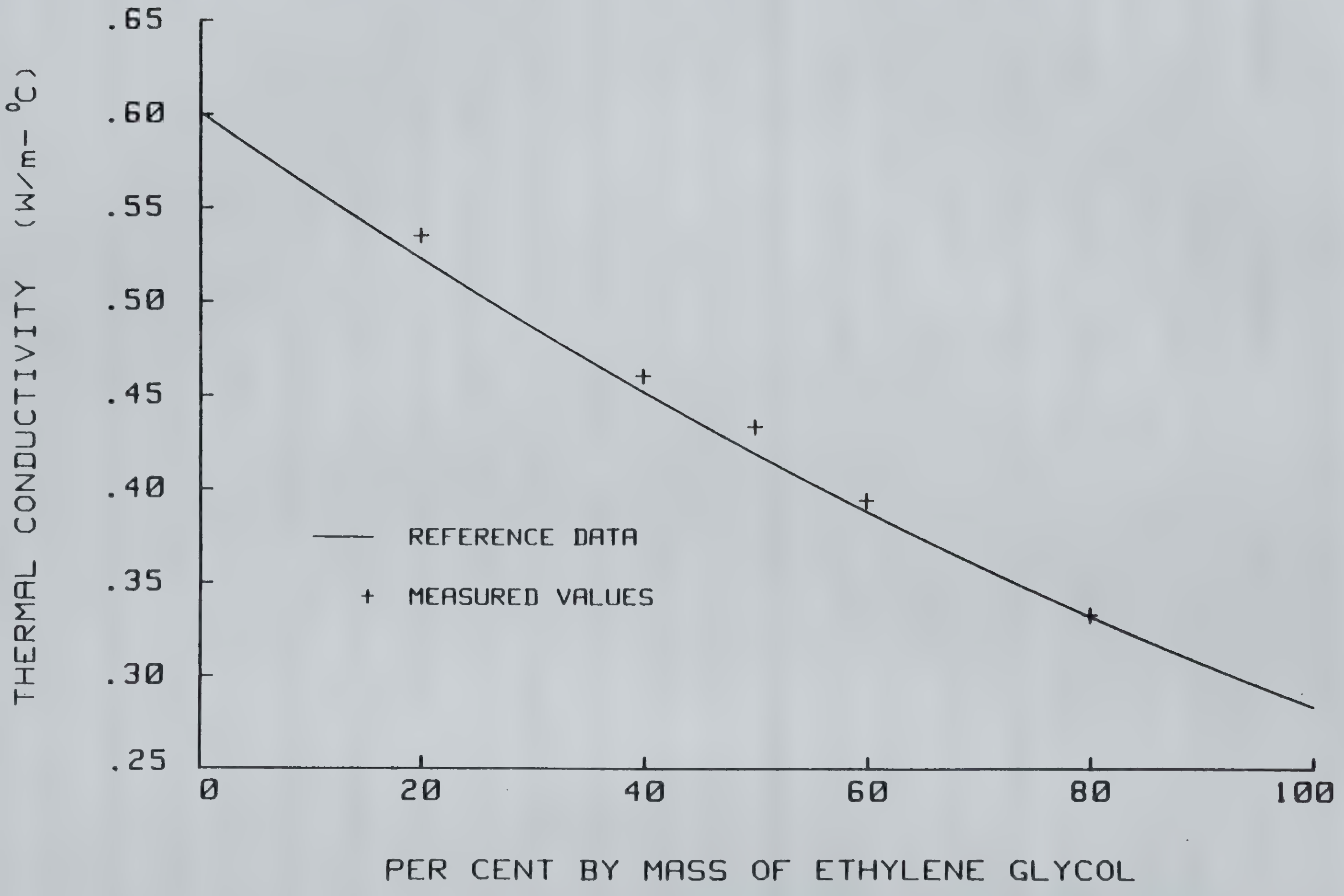


Figure 15. Thermal Conductivity of Aqueous Ethylene Glycol Solutions

Teflon-encapsulated Thermistor

The teflon-encapsulated thermistor was tested using five insulation materials, powdered sulfur, and ten of the 15 liquids measured with the glass-encapsulated thermistor. The five insulation materials included a 100 kg/m^3 fibrous insulation batt, a 50 kg/m^3 fibrous insulation blanket, an alumina-silicate ceramic fiber blanket, a polystyrene sample, and a polymer foam slab. The results for the insulating materials and the higher viscosity liquids are emphasized. The majority of the results for the lower viscosity liquids are purposefully omitted because of poor probe performance associated with testing these materials.

Probe Calibration

The teflon-encapsulated probe was calibrated using glycerin, castor oil, and the ceramic fiber blanket. Representative plots of the V^2 vs $t^{-1/2}$ are given in Fig. 16 for the three calibration materials. The calibration curves of $1/k_b$ vs a are given in Fig. 17. From the centroid of the resulting triangle, the effective probe radius and reciprocal thermal conductivity were determined to be 3.66 mm and 32.4 m-°C/W, respectively.

The choice of the three calibration media was influenced by the findings from preliminary thermal conductivity tests. Using the plots of V^2 vs $t^{-1/2}$ as an indicator, the results were significantly better for the higher viscosity liquids and the insulation materials than for the lower viscosity liquids. Glycerin, castor oil, and ethylene glycol, yielded the best results among the liquids. Of the remaining liquids, only n-heptane and tert butanol gave fair results. Figure 18 illustrates the range of probe performance. The data for the polymer foam insulating material yields the characteristic linear curve while the data for acetone exhibits the randomness typical of the lower viscosity liquids.

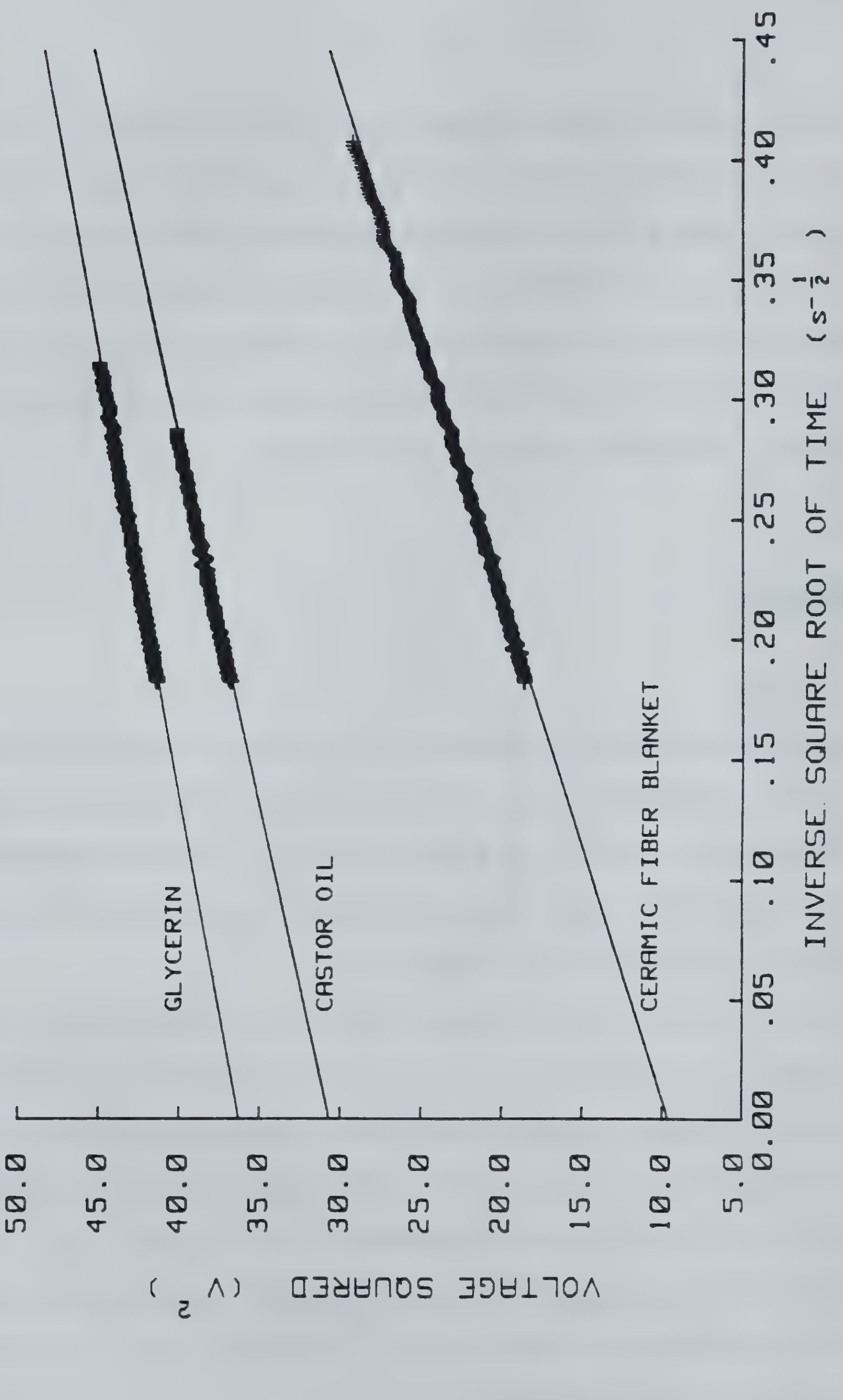


Figure 16. Teflon-encapsulated Thermistor Calibration materials: Characteristic Curves

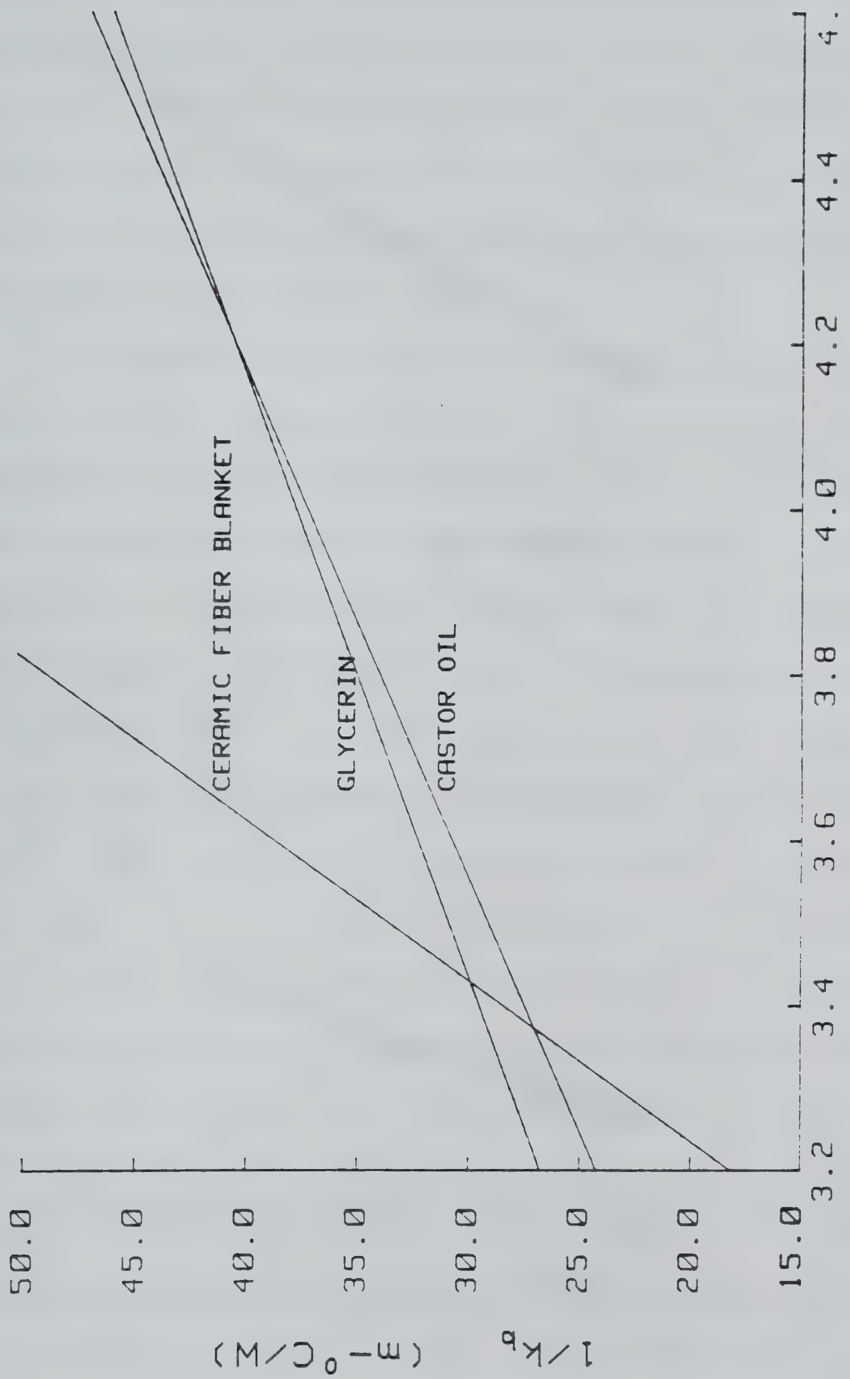


Figure 17. Determination of the Teflon-encapsulated Thermistor Effective Properties

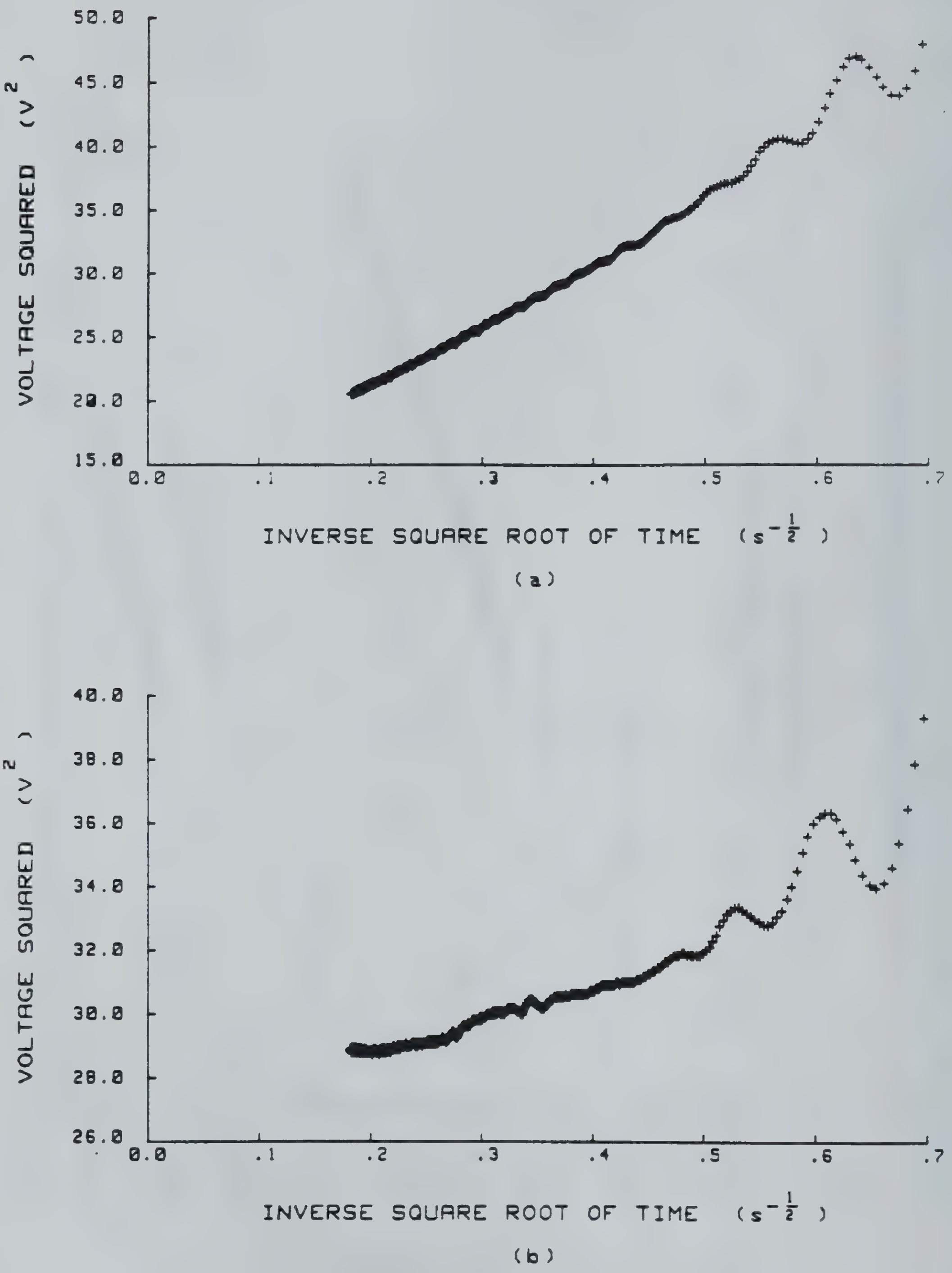


Figure 18. Range of Teflon-encapsulated Probe Performance: (a) Polymer Foam Slab (b) Acetone

The choice of the ceramic fiber blanket as the calibration material for the lower end of the thermal conductivity interval was based on a secondary factor. The reference thermal conductivities of all five insulation materials were measured using the R-MATIC. Therefore, the *k*-value of one material was only as well-known as that of a second. Furthermore, since all five materials are grouped at the lower end of 0.035 W/m-°C, the final choice was based on which material effected the best closure around the embedded thermistor probe. The ceramic fiber blanket was chosen on this basis.

For the teflon-encapsulated thermistor more so than the glass-encapsulated probe, the dependency of the measurement technique on the availability and accuracy of reference materials was demonstrated. The elimination of the lower viscosity liquids because of poor probe performance significantly reduced the number of well-documented materials. In particular, the elimination of distilled water and toluene, the two most extensively tested materials, adversely affected the final results. Left with effectively three viscous liquids and five insulation materials, the probe calibration was further handicapped because the *k*-values of the insulating materials were grouped at 0.035 W/m-°C. Moreover, these *k*-values were estimated to be accurate to ± 5 per cent as compared to quoted uncertainties of less than ±1 per cent for distilled water and toluene [35]. The coupled effect of the insulation materials having higher uncertainties and poor distribution is exhibited in Fig. 19. The intersection point of the calibration curves for the foam polymer and the ceramic fiber blanket changes from 3.19 mm and 17.4 m-°C/W to 4.01 mm and 52.3 m-°C/W as a result of a 5 per cent error in the measured *k*-value of the ceramic fiber blanket (i.e., 0.0343 to 0.0326 W/m-°C). On a per cent basis, this 5 per cent error caused a 25 per cent increase in the probe effective radius and a 200 per cent increase in its reciprocal bead thermal conductivity. The lack of reliable reference materials obviously limits the performance of the calibration-dependent thermistor probe.

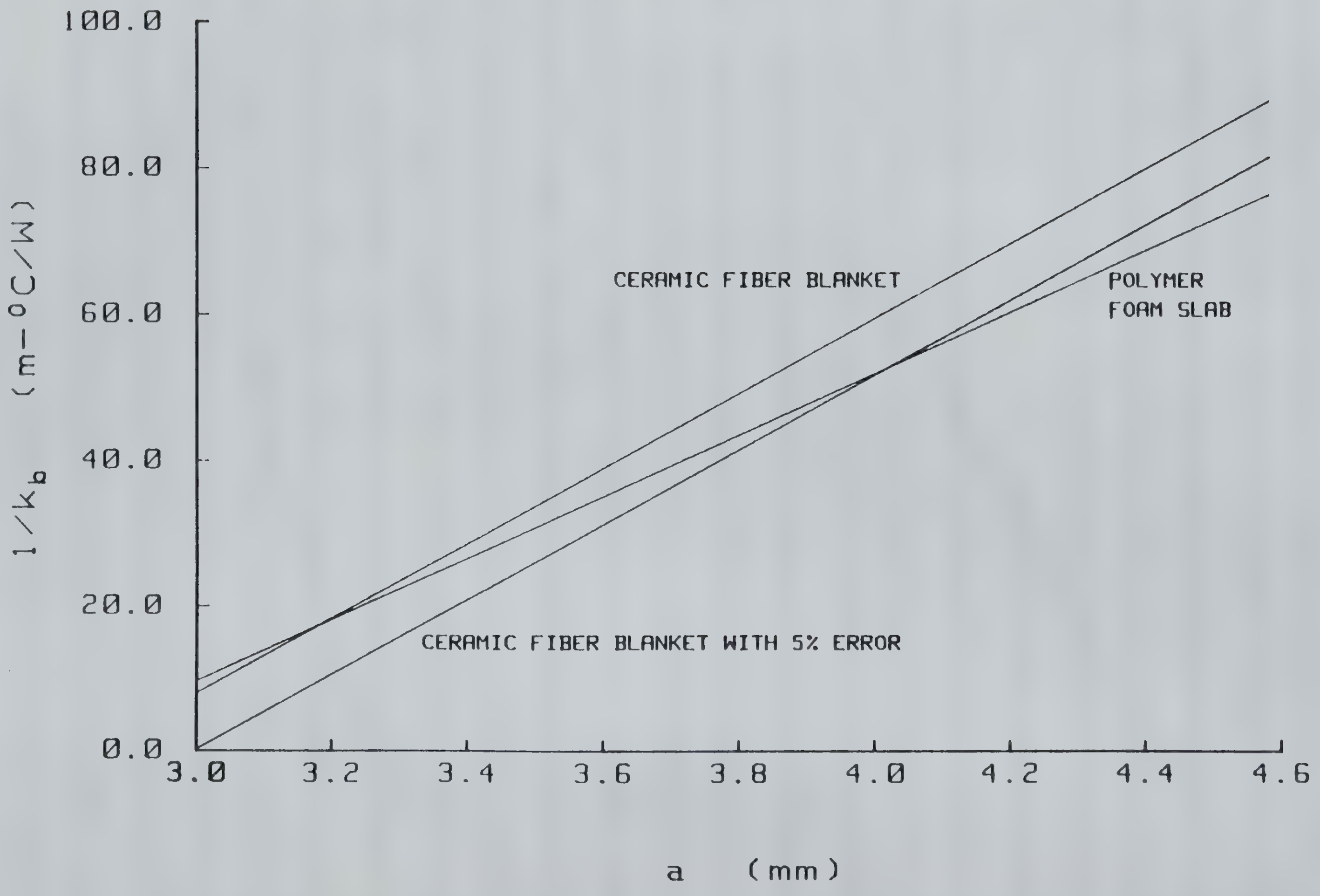


Figure 19. Effects of Poor Reference Materials on Probe Effective Properties

Probe Thermal Conductivity Measurements

Multiple tests were conducted on each material. For the insulation materials, seven tests were conducted on the 100 kg/m³ fibrous insulation batt and the polymer foam slab while four tests were conducted on the other three samples. Three tests were performed on each liquid and powdered sulfur. A representative sampling of the test data for the teflon-encapsulated probe is given in Table 5. Based on the R^2 values, the linear fits again yield good representations for the data. The best results were for the insulating materials. Results for a typical lower viscosity liquid are not included in Table 5 because they are misleading. Specifically, related to the fact that the amount of data used to determine V_{ss}^2 for the lower viscosity liquids was comparatively small, relatively high R^2 values resulted. Referring to Table 5 for materials where the autozero function was enabled, the values of V_{ss}^2 were minimally, although consistently, higher. Although the majority of C values for the higher temperature rise of 3°C were higher, the effect was not systematic. As an example for the 100 kg/m³ insulation batt, the high and low C values correspond to tests with a temperature rise of 2°C, as shown by table entries 6 and 7. Furthermore, the scatter between the seven entries for this material is observed to be random. Finally, for the same material, identical test runs 5 and 6 yielded nearly identical C values of 43838 vs 43800. This result exemplifies the high precision of the measurements.

The thermal conductivities of eleven of the sixteen materials tested are presented in Table 6. The reference values for the insulation materials are from tests using the R-MATIC heat flow meter apparatus on the identical samples. Referring to the results for the three calibration media first, the per cent differences range from -2.8 for castor oil up to 6.1 for the ceramic fiber blanket. These values suggest that calibrating over the relatively large thermal conductivity interval and using materials with different compositions degrades probe measurement accuracy. Despite possibly reaching the application limits of the technique, the results for the majority of the tests are encouraging. The calibrated probe exhibited good

Table 5. Teflon-encapsulated Thermistor Test Data

I.D. No.	Medium	T_i (°C)	ΔT (°C)	Autozero Function	V_{ss}^2 (V^2)	R^2	C (°C/W)
1	100kg/m^3 insulation batt	25.02	3	Disabled	11.314	0.9990	44097
2		25.07	3	Disabled	11.315	0.9992	44012
3		25.06	3	Enabled	11.378	0.9982	43783
4		25.04	3	Disabled	11.345	0.9993	43947
5		24.99	2	Disabled	7.9429	0.9990	43838
6		24.99	2	Disabled	7.9486	0.9990	43800
7		25.01	2	Disabled	7.8058	0.9991	44565
8	n-heptane	25.06	3	Disabled	34.826	0.9859	14304
9		25.06	3	Enabled	35.332	0.9793	14097
10		25.07	2	Disabled	23.967	0.9825	14473
11	ethylene glycol	24.95	2	Disabled	24.910	0.9659	14005
12		24.96	3	Disabled	35.422	0.9785	14128
13		24.95	3	Enabled	35.528	0.8940	14088
14	castor oil	25.01	2	Disabled	21.309	0.9967	16324
15		25.04	3	Disabled	30.650	0.9950	16266
16		25.05	3	Disabled	30.885	0.9858	16139
17	polystyrene	25.09	2	Disabled	6.4307	0.9976	53904
18		25.11	2	Disabled	6.4714	0.9979	53522
19		25.11	3	Disabled	9.1566	0.9981	54278
20		25.12	3	Disabled	9.1705	0.9982	54180
21	powdered sulfur	24.99	3	Disabled	17.934	0.9973	27862
22		24.99	3	Disabled	17.937	0.9964	27855
23		24.99	2	Disabled	12.497	0.9946	27864

Table 6. Teflon-encapsulated Thermistor Thermal Conductivity Results

Medium	Thermal Conductivity (W/m • °C) Thermistor k_t	Reference k_r	Reference No.	Per cent** Difference
castor oil*	0.185	0.180	11	-2.8
glycerin*	0.281	0.292	30,36	3.8
n-heptane	0.251	0.1228	35	-104
sulfur	0.072	--	--	--
ethylene glycol	0.262	0.257/0.28	11/43	-1.9/7.1
tert butanol	0.153	0.119	30	-28.6
100 kg/m³ insulation batt	0.0389	0.0333	R-MATIC	-16.8
polymer foam slab	0.0411	0.0429	R-MATIC	4.2
50 kg/m³ insulation blanket	0.0325	0.0336	R-MATIC	3.3
ceramic fiber blanket*	0.0322	0.0343	R-MATIC	6.1
polystyrene	0.0303	0.0361	R-MATIC	16.1

*designates calibration material

$$**\text{Per Cent Diff.} = \frac{(k_r - k_t)}{k_r} \times 100$$

performance for the majority of the insulating materials. The magnitudes of the per cent differences ranged from 3.3 to 16.8. For the only other higher viscosity liquid tested, ethylene glycol, the measured thermal conductivity splits the two reference values. The result for tert butanol was expected but the large per cent difference for n-heptane was not. In fact, the results for n-heptane are representative of the results for all of the other lower viscosity liquids tested: the measured thermal conductivity was approximately twice that of the reference value. The measured thermal conductivity of the powdered sulfur given in Table 6 is expected to be more representative of the true value than the value obtained using the glass-encapsulated probe (0.016 W/m-°C).

For this study, the calibration and applied tests were essentially interchangeable since materials with known thermal conductivities were used in this study. Related to this circumstance, each material was tested before any final decision was made on which materials would act as the calibration media.

Probe Comparison and Limitations

The overall performance of each probe is directly linked to its characteristic plots of V^2 vs $t^{-1/2}$. Basically, the three different types of materials tested using the probes were relatively high viscosity fluids like castor oil, comparatively low viscosity fluids like n-heptane, and insulation materials like the 100 kg/m^3 fibrous batt.. For these three materials, a characteristic plot for each probe is given in Figs. 20, 21, and 22.

For the more viscous materials like castor oil, Fig. 20, both probes showed good linearity after the initial transients died out. The glass-encapsulated thermistor consistently achieved the desired temperature change faster than the teflon-encapsulated probe. Because of its faster response, the glass-encapsulated probe yielded useful data sooner.

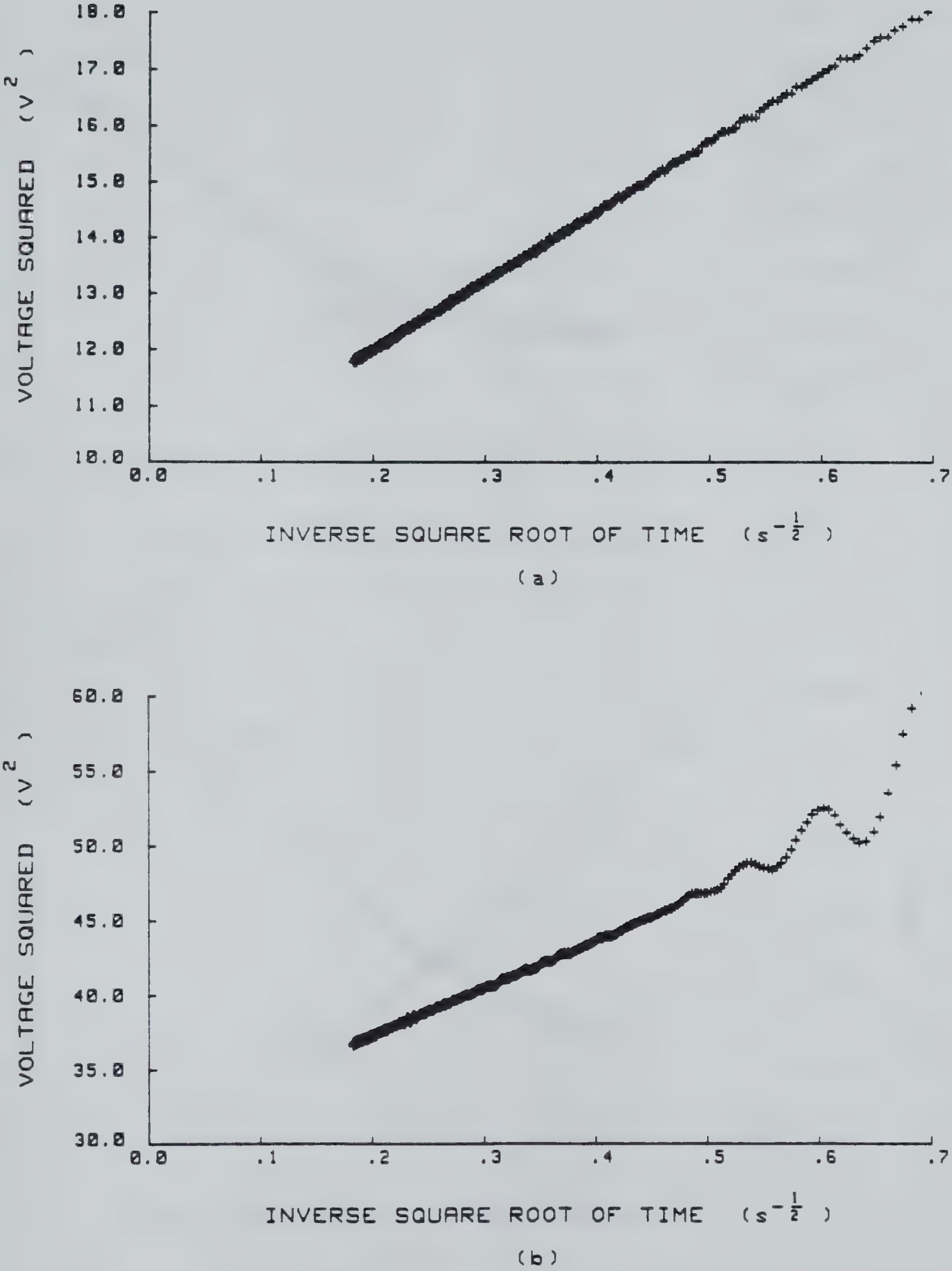
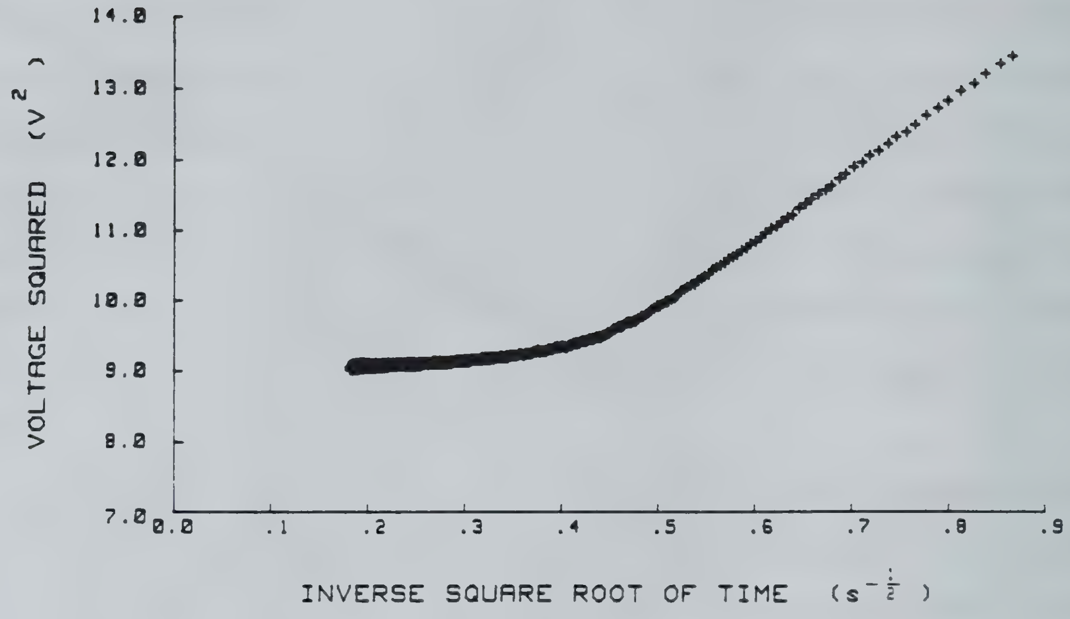
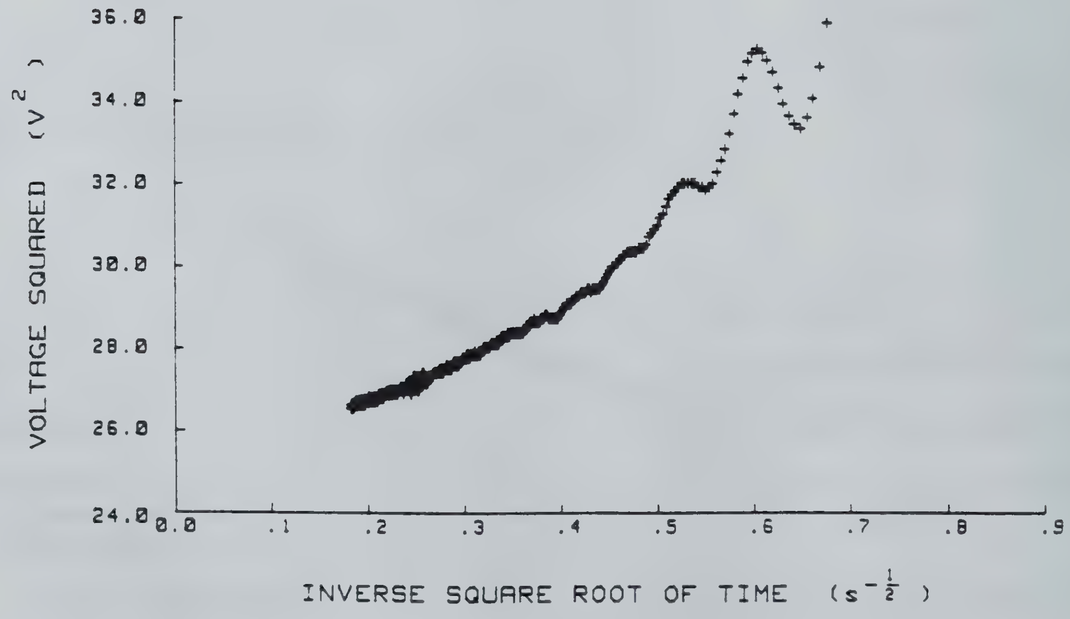


Figure 20. Characteristic Curves for Castor Oil: (a) Glass-encapsulated Thermistor (b) Teflon-encapsulated Thermistor



(a)



(b)

Figure 21. Characteristic Curves for N-Heptane: (a) Glass-encapsulated Thermistor (b) Teflon-encapsulated Thermistor

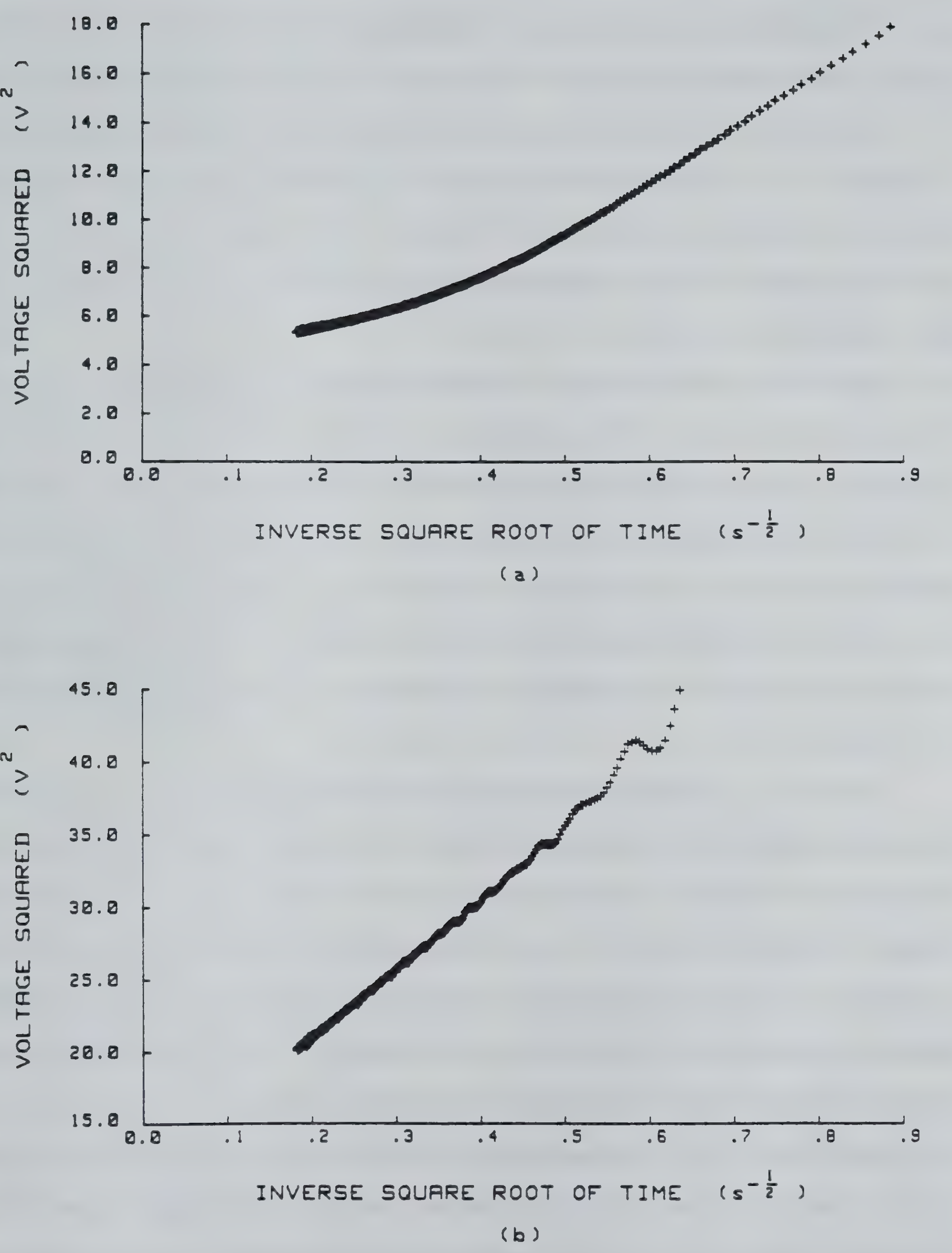


Figure 22. Characteristic Curves for Fibrous Insulation Batt: (a) Glass-encapsulated Thermistor (b) Teflon-encapsulated Thermistor

For the liquids with relatively low viscosities like n-heptane, the comparatively faster responding glass-encapsulated thermistor yielded better results. Referring to Fig. 21, the data for the glass-encapsulated thermistor is smoother than that of the teflon-encapsulated probe. The linear portion of the glass-encapsulated thermistor is also more easily distinguished as compared to the teflon-encapsulated probe. For example, for the glass-encapsulated thermistor the linear portion corresponds to those points between 0.5 and 0.9 on the x-axis whereas the linear portion for the teflon-encapsulated thermistor is largely dependent upon the researcher's judgement.

Using the plot of the glass-encapsulated thermistor as an example, the data graphed to the left of 0.50 on the x-axis depicts a time after which the probe departed from its theoretical operation. This departure is largely the result of the initiation of free convection. When free convection begins, the power dissipated by the probe increases to maintain the specified temperature rise. Free convection was minimized by using relatively small temperature rises. With materials where free convection occurs, it is important to maximize the thermistor time response so that the transients end and the collection of useful data begins within the minimal time interval.

As shown in Fig. 22 for the 100 kg/m^3 fibrous insulation batt, linear plots were typical for data collected from tests with insulation materials. Data for the teflon-encapsulated thermistor are observed to maintain a linear relationship after the initial temperature transients subside. Furthermore, even after 30 seconds, the teflon-encapsulated curve does not exhibit the nonlinearity of the glass-encapsulated thermistor plot. This nonlinearity is believed to indicate appreciable stem losses. The signal wires embedded in the thermistor bead provide a significant conductance for additional heat loss. As in the case with free convection, the power dissipated by the probe increases to offset this heat loss. the thermal conductivities of the insulation materials because of a consistent peculiarity. Referring to Fig. 22, the curve fit for the linear portion of the curve (x greater than 0.45) extrapolated to a negative intercept which is, of course, not possible. The trend towards negative intercepts was also exemplified by the plots for the powdered sulfur. For example, values of V_{ss}^2 for powered sulfur ranged from 0.8 to 1.6 (Table 5). Using a second insulation material, the specified temperature rise was varied to observe how it influenced probe performance. As shown in Fig. 23, the intercept is more negative for the higher temperature rise of 5°C. The reason for this peculiar tendency of the glass-encapsulated thermistor remains unknown.

The glass-encapsulated thermistor was not used to measure

A final observed trend was that the larger, teflon-encapsulated thermistor, for a given medium, always required more power to maintain the specified temperature rise. The characteristic plots of V^2 vs $t^{-1/2}$ cannot be used for direct comparisons because the glass- and teflon-encapsulated thermistors have different resistance ratings (2000 Ω vs 3000 Ω, respectively). The value of C, however, can be used for comparisons since it is directly proportional to the temperature rise divided by the steady-state power, equation 17. Therefore, for a given medium, a higher C value corresponds to a smaller probe power output. Comparing the average C values for castor oil in which both probes exhibited good performance, the value for the glass-encapsulated thermistor is 29748 (Table 1) versus 16293 (Table 5) for the teflon-encapsulated probe. This representative result implies that on average the teflon-encapsulated thermistor required approximately twice as much power as the glass-encapsulated probe during a thermal conductivity measurement.

Unfortunately, the two potential reasons investigated for the differences in probe power requirements suggested that the glass-encapsulated, not the teflon-encapsulated probe, should have the higher power rating. For example, the glass-encapsulated thermistor has the higher effective bead thermal conductivity of 0.057 versus 0.031 W/m-°C for the teflon-encapsulated probe. For a given medium, the higher conductivity probe element appears to conduct heat to the surface of the surrounding medium faster, and, thus, dissipate more energy. Secondly, the diameter of the lead wires embedded in the bead of the teflon-encapsulted thermistor is 0.008 in. as opposed to 0.012 in. for the glass-encasulated bead. Although the lead wires for the teflon-encapsulated probe are made of tinned copper versus a nickle-iron alloy for the glass-encapsulated thermistor, the latter thermistor is expected to act as the better heat sink.

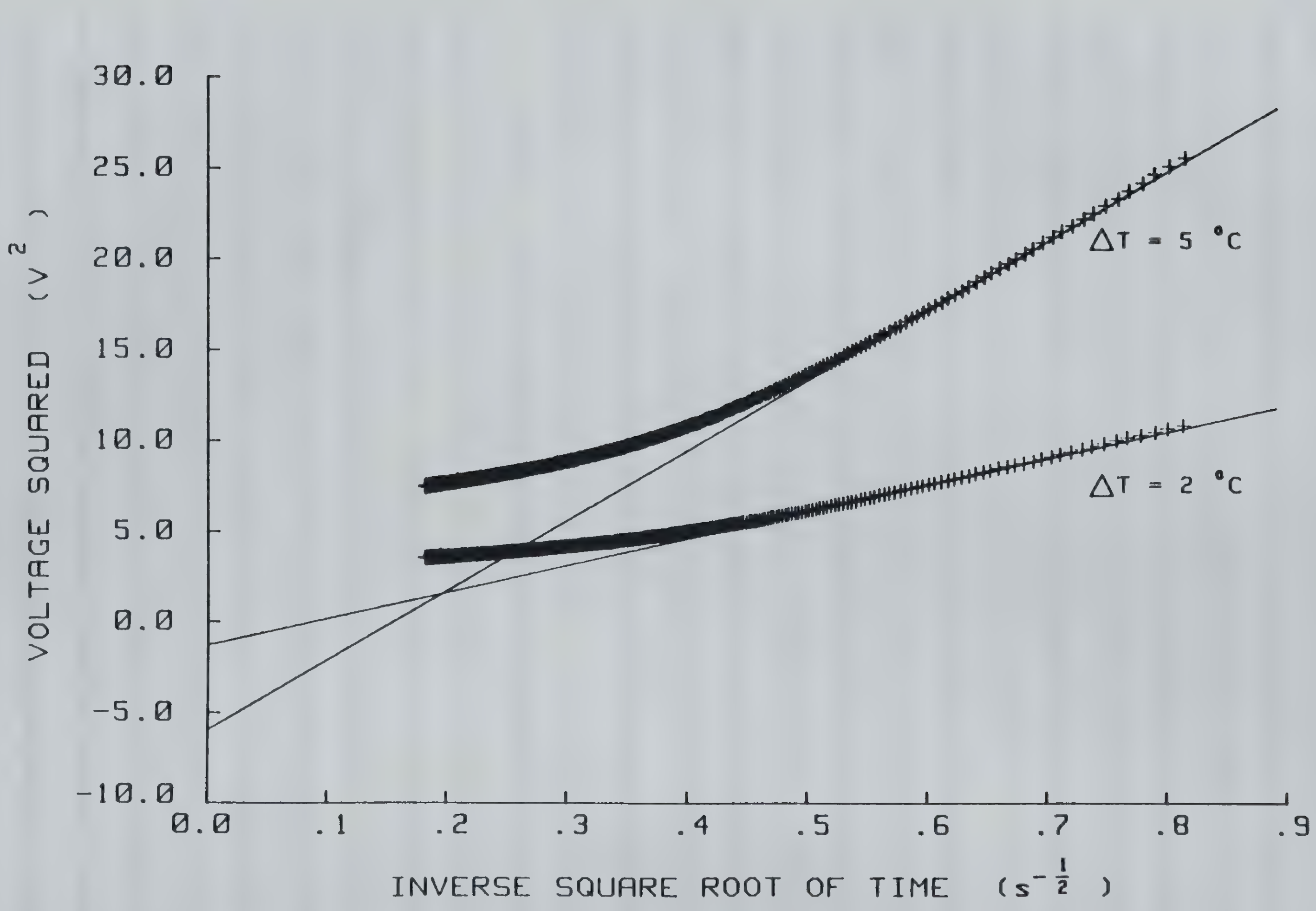


Figure 23. Temperature Rise Effect on the Glass-encapsulated Thermistor Characteristic Curve when Applied to an Insulation Material

The noted peculiarities of each probe type remain unsolved. For example, an investigation into the possibility of a critical ratio for the medium thermal conductivity to the bead thermal conductivity (which is approximately one) for explaining the negative intercept of the glass-encapsulated thermistor when it is applied to insulation material has been unproductive. Analytical results on the effect of this ratio do not explain a negative intercept [4]. The simplest interpretation of the observed peculiarities is that the thermistor-based measurement technique has inherent limitations. Depending upon the material tested, either free convection or stem losses, or both, limit probe measurement performance. From experience, the thermistor appears to be best suited for applications in viscous liquids with relatively higher thermal conductivities (eg., castor oil, glycerin, etc.). The intimate thermal contact and higher thermal conductivities of such liquids help lessen the effect of stem losses while the higher viscosities either delay or even prevent the initiation of free convection.

Summary

The two probes complemented each other in covering the range of materials tested in this investigation. The glass-encapsulated probe was better for measurements in liquids while the teflon-encapsulated probe performed better on the insulation materials. Furthermore, the technique appears to be well suited for interpolating measurements after calibration with materials bracketing the range of interest.

Alternative Probe Development: The Two-Sensor Probe

A thermistor is used as the active probe in the thermal conductivity measurement technique for many reasons. Thermistors are capable of both self heating and temperature sensing. The desired step temperature response is adequately approximated because the thermisor has a relatively low mass and high sensitivity. Encapsulated thermistors electrically insulate the heating element from the surrounding medium.

Thermistors also have inherent shortcomings when used for measuring thermal conductivity. A thermistor has spatially nonuniform heat generation and the volume-averaged temperature is measured. As opposed to hollow, thermistors are solid which increases the thermal capacity. The analytical model also aggregates the encapsulation with the active bead material. These analytical assumptions approximate the operation of the physical probe. Because of the deviations from the analytical model, an alternative small-volume probe was sought.

Description

The two-sensor probe is a second type of small-volume probe. The name two-sensor emphasizes that two components, a separate heating element and temperature sensor on a hollow stem, are integrated to make this probe. The heating element configuration is ideally a sphere; however, a short cylinder also appears acceptable. The surface temperature of the heating element is monitored by an attached temperature sensor (e.g., thermocouple or thermistor). The two-sensor probe is operated in the same mode as the self-heated thermistor, i.e., the surface temperature is quickly elevated and then maintained at a specified temperature by varying the power. With the two-sensor probe, however, the probe-medium interface temperature is measured directly. In comparison, the volume-averaged bead temperature is measured in the self-heated thermistor application.

Theory

The physical system of the two-sensor probe embedded in a test material is analytically modelled as an infinite medium with a spherical cavity. The probe corresponds to the cavity. The boundary condition on the infinite medium is effected by the controlled heat dissipation of the probe. Thus, for this probe configuration, the problem is reduced to investigating only the temperature profile in one material as compared to two for the self-heated thermistor probe application.

Spherical Probe

The ideal two-sensor probe would have a spherical geometry and would be capable of effecting a step temperature change on its surface. For this theoretical probe, the heat conduction equation, the boundary condition corresponding to $r \rightarrow \infty$, and the initial condition are the same as defined for the thermistor model, ie., equations 2, 6, and 8. The only change is in the boundary condition at r=a. Mathematically,

$$T_m(a,t) = T_i + \Delta T_s \qquad t>0 \tag{18}$$

Using the Laplace transform method, the temperature distribution within the medium is

$$T_m(r,t) - T_i = (a/r)\ \Delta T_s\ erfc\left[(r-a)/(2\sqrt{\alpha_m t})\right] \tag{19}$$

The heat rate as a function of time at $r=a$ is

$$q_s(t) = -k_m A_s \frac{\partial T_m(a,t)}{\partial r} = k_m\ \Delta T_s\ 4\pi a \left[1 + \frac{a}{\sqrt{\pi \alpha_m t}}\right] \tag{20}$$

As with the self-heated thermistor probe, the characteristic plot is again the power dissipation as a function of the inverse square root of time. The thermal conductivity of the medium is dependent on the y-intercept while the slope gives its thermal diffusivity.

As observed with the thermistor, any physical probe requires a finite time to achieve the target temperature change. To investigate the effect of the finite rise time, the same problem was solved but now for two different time-dependent boundary conditions. The boundary temperature was modelled approximately as exponential rise and ramp functions. The solution method and results are described in reference 58. When plotted on the same graph with the solution for the ideal step change boundary condition, both time-dependent boundary condition curves are observed to converge to the linear curve of the ideal case. The convergence suggests that the simple mathematical expressions for the thermal conductivity and the thermal diffusivity derived from the ideal case may be employed for the nonideal physical system.

Cylindrical Probe

The primary reason for exploring the potential of the cylindrical two-source probe is because it can be readily built. A small diameter resistance wire could be easily wound around a supporting rod. Accomplishing uniform wire heating over a sphere, on the other hand, is much more difficult.

A cylindrically shaped two-sensor probe was also investigated. The actual probe is visualized as being constructed of a heating element, about one diameter long, wrapped around a lightweight supporting rod. As with the spherical two-sensor probe, a temperature sensor would be mounted on the heating element. The physical system of this cylindrical two-sensor probe dissipating heat to a surrounding medium has been analytically modelled [58]. This model is used to solve for the temperature distributions in the rod and medium using an implicit finite-difference technique.

The pending analysis should indicate if the plot of the power dissipation as a function of the inverse square root of time has the characteristic linear shape. If such a relationship is observed, the possibility exists for using the mathematical results from the ideal spherical geometry case along with an effective radius. The probe would be calibrated to determine its effective radius.

Application Considerations

A rather primitive two-sensor probe was used to answer some initial application questions. This probe consists of a 3-mil type-E thermocouple attached to a teflon-encapsulated thermistor. Using a fine thread winding, as shown in Fig. 24, the position of the thermocouple junction is centered on the encapsulated bead. The basic test measurement procedure is the same as for the thermistor. For the new application, however, the thermistor is used only as a heating element. The attached thermocouple is now used for temperature sensing.

A problem with using the thermistor, or a heating element with similar characteristics, was realized from the initial tests. Since thermistor resistance is temperature dependent, its power dissipation cannot be accurately determined from only knowing the current. Consequently, the thermistor voltage and the thermocouple emf were both measured. The overall result was a reduction in the sampling rate from 21.6 Hz to 3.9 Hz. As observed with the thermistor, the effectiveness of the control strategy deteriorates, and the amount of collected data is greatly curtailed. To limit measurements to temperature sensing, the active heating element of a two-sensor probe should have a very small temperature coefficient. A second, although less substantiated result, was that a thermocouple may lack the resolution and precision needed for sensing the relatively small surface temperature rise of 2°C. Another type of thermistor, possibly a chip type thermistor, may be a better alternative.

High resistivity, fine diameter, and an insulating coating are the desired characteristics of the heating element resistance wire. Maximum current output and heating element total resistance set the maximum power rating of the heating element. The resolution of the current output from the HP power supply is dependent upon its maximum current setting. In order to maximize current resolution, the largest resistance element, and thus the wire with the highest resistivity, is sought. Fine diameters, which are associated with high resistivities, also help to limit the total thermal mass of the probe. A wire with an insulating coating would

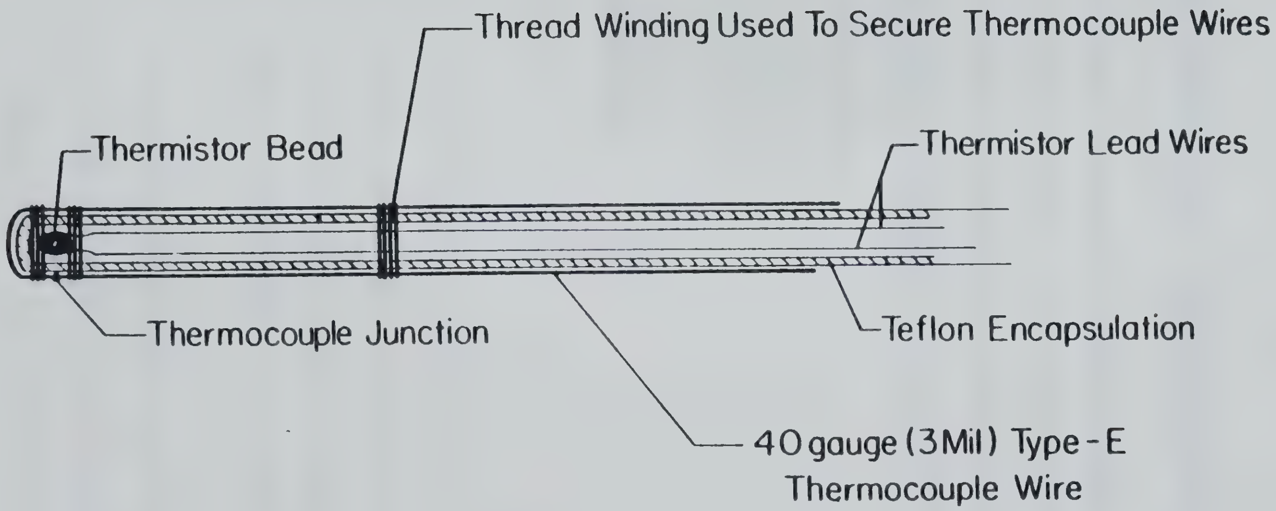


Figure 24. First Generation Two-Sensor Probe

permit closely spaced winding and use of the probe in an electrically conductive medium. From a review of manufacturer's literature, suitable wire types are available.

Project Status

Due to time constraints, the investigation with the two-sensor probe was limited to analytical investigations which are not part of this thesis. The work consisted of analytically evaluating the cylindrical probe and conducting an analysis to determine the wire requirements for both heating element geometries. Once design parameters are determined, a prototype probe would be built.

Conclusions and Recommendations

The following conclusions summarize the capabilities of the thermistor-based measurement technique.

Conclusions

- An all-digital data acquisition and control system was successfully developed. The integral control strategy closely controlled the temperature response of the self-heated thermistor. Following a typical 30-second thermal conductivity test, the *k*-value of the test sample was available in approximately 15 minutes.

- The sampling rate did not influence the final thermal conductivity values for well-behaved materials. For such materials, attaining an initial step change was not highly important. The response time of the thermistor was important when free convection in liquids or stem losses in insulation materials occurred.

- The effectiveness of the thermistor-based measurement technique is strongly dependent on the availability of standard reference materials. The two effective probe properties are determined by calibration using reference materials. Ideally, three calibration materials should bracket and equally divide the thermal conductivity interval of interest.

- The range of the thermal conductivity interval should span a wide enough interval to avoid similar calibration curves. As with the tightly grouped insulation materials, the effective probe properties from similar calibration curves are strongly influenced by the uncertainties in the thermal conductivities of reference materials.

- The glass- and teflon-encapsulated thermistor probes complemented each other for the group of twenty-one materials tested. The former performed better on the liquids with the majority of the measurements differing by less than 8 per cent when compared to reference values. The teflon-encapsulated thermistor performed better on the insulation materials. The differences between the *k*-value of the insulation materials measured using the teflon-encapsulated thermistor and the R-MATIC heat flow meter apparatus ranged from 3 to 17 per cent.

- Each probe exhibited unique limitations in measuring all the test materials. This result supports validating a given calibrated probe with materials which bracket the range of interest.

- The overall best results were obtained when the probe was used as an interpolating instrument on materials with similar compositions.

Recommendations

The development of the cylindrical two-sensor probe should be continued. The results will indicate the relative advantages of pursuing this probe type vs continued refinement of the thermistor-based technique. The advances made using the thermistor-based technique should enhance the development and evaluation of the two-sensor probe.

The identification of standard reference materials, especially bracketing the range of insulation materials, is needed. The effectiveness of relative measurement techniques like the thermistor and the cylindrical two-sensor probe are dependent on the availability of standard reference materials.

The use of the thermistor-based apparatus for measuring thermal diffusivity should be validated. A refinement of the analytical model for the thermistor's operation may also be beneficial. For example, modified coupled heat conductions equations containing a heat generation function which accounted for the thermistor's initial transients could possibly be solved.

Appendix A.

Three programs are integral parts of the thermistor thermal conductivity measurement technique. These programs comprise the bulk of this appendix. The listings contain a large number of comment statements which help explain the operation of each program. Because of the detail given to commenting the listings, only the procedural aspects of using these three programs are described.

Each program has a unique task. Related to this task, each program is written using a different language. The main program, THERMAC.TEXT, embodies the majority of the logic used to conduct a thermal conductivity test. This program is written using IEM FORTRAN77. The second program, HPIO.TEXT, is actually a module which contains subroutines enabling I/O between the computer and the data acquisition and control equipment. This second program is accessed by the main program during execution of a thermal conductivity test. HPIO.TEXT is written using 3.0 HP Pascal. The compiled versions of each of the two programs -- identified by a .CODE suffix -- are the actual programs executed by the computer. The third program, CONVERSION, converts an ASCII data file generated during a thermal conductivity test into a structured BASIC BDAT equivalent file. This conversion is required in order to upload the raw data into a copyrighted regression analysis. CONVERSION is written using 3.0 HP BASIC. Each of these files will be further described within the outline of the test procedure.

Within the Pascal environment, many softkeys are available for accessing features of the system. These softkeys are identified within the command line (located at the top of the CRT) by the capitalized letter of the key word. For example, the command line lists the key word "Editor" which is accessed by pressing the E on the keyboard. Some of the key words are included within the explanation of the test procedure which follows. These key words are set apart using quotations when they are first used.

Thermal Conductivity Test Procedure

The FORTRAN77 thermal conductivity program is executed within the HP Pascal environment. Once the computer has been booted, one system default should be checked and possibly updated. The "What" command is used to access a listing of the system defaults which include, among others, the defaults for the "Compiler", the Editor, the "liBrary", and the "System" volume. With respect to running a compiled thermal conductivity program like THERMAC.CODE, the liBrary default must be set to the IEM FORTRAN77 library, named FTNLIB. This FORTRAN library must be on-line when the thermal conductivity program is first "eXecuted". Assuming an update is needed and the library is stored on the hard disc volume V11, the new liBrary default should be entered as V11:FTNLIB., where the trailing period is required. With the liBrary default correctly set, the operator exists the list of system defaults by using the "Quit" option.

Two programs are loaded into the computer's RAM memory before the thermal conductivity program is eXecuted. The first program is part of the IEM FORTRAN77 library. Using the "P-load" softkey, the operator enters at the prompt, V11:1O. (note the trailing period again). The second P-loaded program is the Pascal I/O module, HPIO.CODE. Assuming this module is also stored on the hard disc volume V11, the operator enters V11:HPIO.CODE (note no trailing period after the suffix). With these two programs in RAM, the thermal conductivity program is initiated by eXecuteing the program, V12:THERMAC.CODE (example assumes the program is stored on the hard disc volume V12).

The thermal conductivity program permits the user to set the maximum current output and prompts him for specific test information. With the HP 3466A multimeter connected to the terminals of the power supply, the full-scale and zero outputs are set by using the appropriate screw adjustments on the power supply programmer. The prompts for test information are adequately explained within the execution of the program. Suggestions for numerical inputs, like the feedback gain setting, are included with a specific prompt. Following the transient test interval, the pertinent data - voltage squared, thermistor temperature, and time - are stored on an Pascal-initialized diskette. The computer will prompt the user to place the diskette in the left internal disc drive, #4. The data is always stored on the diskette under the filename VTT. Notably, the format of this data file is a special, non-ASCII type. The format is important because the copyrighted statistical software package used for follow-up data reduction requires the data to be in a structured BASIC BDAT file.

Data Conversion

The raw data file is converted into its ASCII equivalent and then into its structured BDAT format. The conversion to an ASCII format is achieved using the "Filer" of the Pascal system. By pressing the F-softkey, a group of commands are accessed including the "Translate" and "Remove" options. The user first Translates the data file by answering the two prompts with: V3:VTT and V3:filename.ASC, (V3: is the default volume name given to a floppy diskette during the Pascal formatting routine). The chosen filename of the data file can be no more than seven characters in length. The suffix .ASC must be included on each new filename. In preparation for a second thermal conductivity test, the original data file V3:VTT should be Removed at this time. The data disc with the ASCII files is transformed into the structured

BDAT file by using the program CONVERSION. Having rebooted the computer using HP 3.0 BASIC, the user loads and runs CONVERSION. A message within the program instructs the user about the placement of the source ASCII and the target BASIC-initialized floppy diskettes. An initial prompt permits the cataloging of either diskette. Once the user answers the prompts for the source and target filenames, the conversion process is completed in approximately a minute. The original data is now in a form which is readily uploaded for analysis using the copyrighted statistical software.

Data Reduction

A brief review of the minimal steps required to plot the characteristic curve of V^2 vs $t^{-1/2}$ using the capabilities of the statistical package are outlined below.

- The program CONVERSION is first removed from memory by executing the command: SCRATCH A.
- With the diskette labelled BASIC STATISTICS placed in the right-hand internal drive, execute: LOAD "AUTOST: INTERNAL", 1.
- Answer the first few prompts accordingly. The prompt for the type of data should be answered with a 1 for RAW DATA.
- The prompt for the source of the data should be answered with a 2 for MASS STORAGE.
- The prompt regarding the possibility of the data file being the SCRATCH FILE (filename: DATA) should be answered with an N.

- The prompt for the physical location and filename of the data file is answered (assuming the data diskette is in the left-hand internal drive) by entering: filename:INTERNAL,4,1.

- An N response should be given to the prompt regarding if the data file was original stored by the BASIC STATISTICS program.

- The next three main prompts should be answered accordingly. The number of observations originally recorded is printed as part of the original test data and also during the execution of the program CONVERSION. Answers the follow-up prompts for the names of the variables with: V**2, TEMP, and TIME.

- Answer the following three Y/N prompts with Y. The structure of the data is all entries for the first variable followed by all entries of the second variable, and so on. Answer the fourth prompt in this sequence with a Y when ready.

- A peculiarity of this uploading process is that the first observation is in error. This observation, which corresponds to the test status at time equal to zero, may either be corrected or deleted using the EDIT feature of the software.

- The TRANSFORM feature of the statistical package is used to develop a new variable, the inverse square root of time, given the raw TIME data. Use the Algebraic Option (1) and the first listed equation. Store the new variable as variable #4.

- Further choices of creating subfiles or deleting observations are available using the capabilities of the software.

- Finally, the actual statistical analysis and data plotting is initiated by accessing the ADVanced STATistics software. Specifically, after pressing the ADV STAT softkey, two menus will appear consecutively. In response to the first list, enter 4 for Regression Analysis. In response to the second list, enter 3 for Polynomial Regression.

- Answer the prompts accordingly. The basic sequence involves specifying the subfile number (if any exist), and the independent and the dependent variables. The user requests a plot to be made (usually on the CRT), and inputs the parameters for the plot. Questions and results related to the regression analysis follow the data plotting sequence. With respect to these follow-up questions, the desired order of regression is 1 and the choice of a confidence coefficient is usually 99.

```
C        1         2         3         4         5         6         7
C23456789012345678901234567890123456789012345678901234567890123456789012
C
C            PROGRAM FILENAME:  V12:THERMAC.TEXT
C
C  THE A IN THE FILENAME THERMAC INDICATES THAT THIS VERSION OF THE
C  THERMISTOR CALIBRATION PROGRAM IS CONFIGURED TO RECORD EVERY (ALL)
C  DATA OBSERVATION.  THIS PROGRAM RECORDS THE INITIAL TRANSIENT
C  RESPONSE OF THE PROBE.
C
C  THE C IN THE FILENAME INDICATES THAT THIS VERSION OF THE
C  PROGRAM CONTAINS AN EXCESSIVE AMOUNT OF COMMENT STATEMENTS.
C
C  THIS PROGRAM MONITORS THE THERMISTOR VOLTAGE, VT, AND HOLDS THE
C  RESISTANCE, R_HOT, CONSTANT BY VARYING THE CURRENT.  THE CURRENT
C  IS SUPPLIED BY THE COUPLED HP 6186C POWER SUPPLY AND HP 59501B
C  POWER SUPPLY PROGRAMMER.
C
C  THIS PROGRAM IS WRITTEN USING IEM FORTRAN 77; THE INTERFACING OF THE
C  HP 9836 AND THE DATA AQUISITION SYSTEM IS ACHIEVED BY ACCESSING A
C  FILE WRITTEN IN HP PASCAL 3.0 (FILENAME:  HPIO).
C
C  THE FOLLOWING IMPORT COMMANDS ARE USED TO ACCESS PRE-WRITTEN MODULES
C  (IE., PROGRAMS).  WITHIN IEM'S FRAMEWORK, A GROUP OF MODULES COMPOSE
C  A FILE.  THE MAJORITY OF THESE MODULES ARE FOUND WITHIN THE FILES ON
C  THE IEM LIBRARY DISKETTE.  A LISTING OF WHICH MODULES MAKE-UP THE
C  DIFFERENT FILES ARE LISTED IN THE IEM FORTRAN MANUAL ON PAGE 4-2.
C  INFORMATION ON THE CAPABILITIES OF THE DIFFERENT CANNED MODULES
C  MAY BE INDIRECTLY DETERMINED BY READING CHAPTER 9 OF THE SAME
C  MANUAL.
C  THE VERSION OF THE IEM LIBRARY USED FOR THIS PROGRAM IS 3215.
C  A RECENTLY PURCHASED FORTRAN77 UPDATE HAS A FEW DIFFERENCES FROM
C  VERSION 3215 AND WAS NOT USED IN ANY OF THE PROGRAMS WRITTEN BY
C  BPD.
```

```
C  THE PREFIXES V11 AND V12 CORRESPOND TO THE FIRST TWO VOLUMES ON
C  THE HP 9154B 20 MBYTE HARD DISC (REFER TO BPD NOTEBOOK #2).
C  THE MODULE V12:HPIO.CODE IS THE PASCAL PROGRAM THAT PERMITS I/O.
C
$IMPORT HPIO IN V12:HPIO.CODE
$IMPORT SYSDEVS IN V11:INTERFACE
$IMPORT A804XDVR IN V11:INTERFACE
$IMPORT SYSGLOBALS IN V11:INTERFACE
$IMPORT IODECLARATIONS IN V11:IO
$IMPORT GENERAL_1 IN V11:IO
$IMPORT GENERAL_2 IN V11:IO
$IMPORT HPIB_0 IN V11:IO
$IMPORT HPIB_1 IN V11:IO
$IMPORT HPIB_2 IN V11:IO
C
C  THE FOLLOWING STATEMENT IS A COMPILER DIRECTIVE THAT DIRECTS
C  THE COMPILER TO NOT FLAG SECONDARY NON-ANSI FEATURES (EG.,
C  SYBOLIC NAMES WITH MORE THAN SIX CHARACTERS).
$ANSI OFF
      PROGRAM THERMSC
      CHARACTER*81 STR_1
      CHARACTER*5 MED
C  THE FOLLOWING EXTERNAL STATEMENT ACCESSES THREE UNIQUE HP PASCAL
C  FUNCTIONS.  INFORMATION ON THESE FUNCTIONS AND THE METHOD USED
C  TO ACCESS THEM MAY BE FOUND BY READING ABOUT THE EXTERNAL COMMAND
C  AND REVIEWING PAGES 9-6,9-7,9-32, AND 9-33 IN THE IEM MANUAL.  THE
C  PASCAL 3.0 PROCEDURE LIBRARY MANUAL GIVES INFORMATION ON THESE
C  TIMING RELATED FUNCTIONS ON PAGES 216 TO 219.  ALL THREE OF THESE
C  FUNCTIONS ARE PART OF THE MODULE SYSDEVS.
      EXTERNAL BEEP,SETSYSTIME,SYSCLOCK
      INTEGER WORD,MED1,COUNT,ILOOP,SYSCLOCK,FLAGG
      REAL CONST1,WWORD
      COMMON /BLOCK1/ WWORD,COUNT,TTIME,VT,R_HOT,CURRENT,AA,BB
      COMMON /BLOCK2/ ILOOP,FLAGG
      COMMON /BLOCK3/ VT_TIME(1200,6)
C
C  BEEP JUST MAKES THE COMPUTER BEEP.
C  SETSYSTIME RESETS THE INTERNAL CLOCK OF THE 9836 TO ZERO.
C  SYSCLOCK RETURNS AN INTEGER REPRESENTING THE NUMBER OF
C    CENTISECONDS SINCE THE CLOCK WAS RESET.
C  THE VARIABLES WORD AND WWORD ARE THE INTEGER AND REAL VALUES OF
C    SAME VARIABLE:  THE DIGITAL WORD (2000 - 2999) REPRESENTING THE
C    DESIRED OUTPUT FROM THE POWER SUPPLY.
C  MED1 IS AN INPUT VARIABLE WHICH DENOTES THE SURROUNDING MEDIUM
C    BEING TESTED.
C  COUNT INDICATES THE NUMBER OF READINGS RECORDED.
C  ILOOP INDICATES THE NUMBER OF UPDATES OF THE CURRENT THAT WERE MADE
C    DURING THE TEST RUN.
C  FLAGG IS A FLAG TO TELL WHEN THE RUN HAS BEEN TERMINATED.
C  CONST1 IS THE GAIN SETTING ON THE INTEGRAL CONTROLLER.
C  TTIME IS THE TIME IS SECONDS.
C  VT IS THE MEASURED SELF-HEATED THERMISTOR VOLTAGE.
C  R_HOT IS THE RESISTANCE OF THE SELF-HEATED THERMISTOR.
C  CURRENT IS THE AMPERAGE SUPPLIED TO THE THERMISTOR IN MA.
C  AA IS THE INTERCEPT CONSTANT OF THE THERMISTOR'S T VS LN(R) FIT.
C  BB IS THE SLOPE CONSTANT OF THE THERMISTOR'S T VS LN(R) LINEAR FIT.
C  VTTIME IS THE ARRAY THAT STORES THE SIX PERTINENT RUN VARIABLES.
C
C  INITIALIZING VARIABLES.
      COUNT=0
      ILOOP=0
      FLAGG=0
      ERROR_INT=0
C  ERROR_INT IS THE INTEGRATED ERROR OF THE INTEGRAL CONTROLLER.
C
C  CLEARING THE HP BUS -- 709 IS THE HP 3497A DATA ACQUISITION SYSTEM
C  AND 706 IS THE HP 59501B POWER SUPPLY PROGRAMMER
      CALL MY_CLEAR(709)
      CALL MY_CLEAR(706)
C
C  SETTING THE ZERO POINT AND THE FULL SCALE CURRENT ON THE
C  HP 59501B POWER SUPPLY PROGRAMMER
C
   1  WRITE(*,2)
C  THE * REPRESENT THE CRT
   2  FORMAT(66(/))
      PRINT *,'     POWER SUPPLY PROGRAMMER INITIAL SET POINT CHECK'
      PRINT *,' '
      PRINT *,'     USE THE HP 3466A DIGITAL MULTIMETER IN THE DC'
      PRINT *,'                     CURRENT MODE'
      PRINT *,'     (NOTE:  DISCONNECT ALL PROBE LEADS FROM THE DC'
      PRINT *,'     CONSTANT CURRENT SOURCE BEFORE CHECKING SET POINTS)'
      PRINT *,' '
      PRINT *,' '
      PRINT *,'#1 ==> ZERO ADJUST (CONTROL WORD = 2000)'
      PRINT *,'#2 ==> FULL SCALE ADJUST (CONTROL WORD = 2999)'
      PRINT *,'#3 ==> HALF SCALE CHECK (CONTROL WORD = 2500)'
      PRINT *,'#4 ==> FINISHED: .CONTINUE WITH THE CALIBRATION'
      PRINT *,' '
      WRITE(*,'(A\)') 'ENTER THE NUMBER OF THE DESIRED CONDITION.  '
      READ(*,'(I1)')I_ADJ
      IF (I_ADJ .EQ. 1) WORD=2000
      IF (I_ADJ .EQ. 2) WORD=2999
      IF (I_ADJ .EQ. 3) WORD=2500
      IF (I_ADJ .EQ. 4) GOTO 3
C
C  MY_WRITESTRING IS A PASCAL SUBROUTINE (FOUND IN HPIO) THAT PERMITS
C  A CONTROL WORD TO BE WRITTEN TO THE HP POWER SUPPLY PROGRAMMER
      CALL MY_WRITESTRING(706,WORD)
      GOTO 1
   3  WRITE(*,2)
C  2000 CORRESPONDS TO ZERO CURRENT OUTPUT
```

```
      WORD=2000
      CALL MY_WRITESTRING(706,WORD)
      CALL MY_CLEAR(706)
      PAUSE '   *****  AT THIS TIME, RECONNECT THE PROBE WIRING *****'
      WRITE(*,2)
C
C  REMINDER . . . . THE DATA FILE THD: VTT MUST BE CONVERTED TO ITS
C  ASCII EQUIVALENT BEFORE RUNNING ANOTHER CALIBRATION CASE
C
      PRINT *, '     BEFORE CONTINUING : DID YOU RENAME THE LAST DATA FILE TO ITS'
      PRINT *, '     ASCII EQUIVALENT?'
      PRINT *, ' '
      PRINT *, '     IF NOT, AT THIS TIME TERMINATE THIS RUN AND GO TO THE FILER AND:'
      PRINT *, ' '
      PRINT *, '     (1) TRANSLATE THE FILE THD:VTT TO A READILY IDENTIFIABLE
     ASCII EQUIVALENT'
      PRINT *, '         (IE. WATER_14.ASC -- REMEMBER THE .ASC).'
      PRINT *, ' '
      PRINT *, '     (2) REMOVE THE FILE THD:VTT FROM THE DATA DISC; THIS
     IS ALWAYS THE NAME'
      PRINT *, '         OF THE IEM FORTRAN77 GENERATED DATA FILE.'
      PRINT *, ' '
      PRINT *, ' '
      PRINT *, ' '
      PAUSE
      WRITE(*,2)
C
C  BEGIN THE CALIBRATION PROCEDURE
C     COLLECT USER INPUT DATA
C
      PRINT *,'#1 ==> DISTILLED WATER'
      PRINT *,'#2 ==> AIR'
      PRINT *,'#3 ==> CASTOR OIL'
      PRINT *,'#4 ==> GLYCERIN'
      PRINT *,'#5 ==> ETHYL ALCHOL'
      PRINT *,'#6 ==> TOLUENE'
      PRINT *,'#7 ==> 100  ETHYLENE GLYCOL'
      PRINT *,'#8 ==> TERT BUTANOL'
      PRINT *,'#9 ==> ACETONE'
      PRINT *,'#10 ==> SULFUR'
      PRINT *,'#11 ==> N-HEPTANE'
      PRINT *,'#12 ==> METHANOL'
      PRINT *,'#13 ==> ARMAFLEX
      PRINT *,'#14 ==> NBS INSULATION BATT'
      PRINT *,' '
      WRITE(*,'(A\)')'ENTER THE NUMBER CORRESPONDING TO THE CORRECT
     +MEDIUM.   '
      READ(*,'(I2)')MED1
      PRINT *, ' '
      PRINT *, ' '
      WRITE(6,10)
C  UNIT 6 IS THE HP PRINTER.
  10  FORMAT('TEST MEDIUM:  ',\)
      IF (MED1 .EQ. 1) WRITE(6,15)'DISTILLED WATER'
      IF (MED1 .EQ. 2) WRITE(6,15)'AIR'
      IF (MED1 .EQ. 3) WRITE(6,15)'CASTOR OIL'
      IF (MED1 .EQ. 4) WRITE(6,15)'GLYCERIN'
      IF (MED1 .EQ. 5) WRITE(6,15)'ETHYL ALCHOL'
      IF (MED1 .EQ. 6) WRITE(6,15)'TOLUENE'
      IF (MED1 .EQ. 7) WRITE(6,15)'100  ETHYLENE GLYCOL'
      IF (MED1 .EQ. 8) WRITE(6,15)'TERT BUTANOL'
      IF (MED1 .EQ. 9) WRITE(6,15)'ACETONE'
      IF (MED1 .EQ. 10)WRITE(6,15)'SULFUR'
      IF (MED1 .EQ. 11)WRITE(6,15)'N-HEPTANE'
      IF (MED1 .EQ. 12)WRITE(6,15)'METHANOL'
      IF (MED1 .EQ. 13)WRITE(6,15)'ARMAFLEX'
      IF (MED1 .EQ. 14)WRITE(6,15)'NBS INSULATION BATT'
 15   FORMAT(A)
```

```
      WRITE(*,2)
      PRINT *, ' '
      PRINT *, ' '
      PRINT *, 'OPTIONS: #1, #3, #7, #9, #14'
      WRITE(*,'(A)')'ENTER THE THERMISTOR ID NUMBER.'
      READ(*,'(I2)')NTH
      WRITE(6,16)NTH
 16   FORMAT('THERMISTOR ID NUMBER:  ',I2)
C
C  THE FOLLOWING ARE THE CONSTANTS FOR A LINEAR CURVE FIT OF THE
C  THERMISTOR'S TEMPERATURE AS A FUNCTION OF ITS NATURAL LOG OF
C  RESISTANCE.
      IF (NTH .EQ. 1) THEN
      AA=206.708
      BB=-22.6781
      END IF
      IF (NTH .EQ. 3) THEN
      AA=206.47445
      BB=-22.6413
      END IF
      IF (NTH .EQ. 7) THEN
      AA=211.9974
      BB=-27.09895
      END IF
      IF (NTH .EQ. 9) THEN
      AA=212.3583
      BB=-25.14037
      END IF
      IF (NTH .EQ. 14) THEN
      AA=211.58059
      BB=-26.93877
      END IF
      PRINT *, ' '
      PRINT *, ' '
C
C  THE FEEDBACK GAIN IS SOMETHING THAT YOU WILL HAVE TO PLAY WITH.  THE
C  GAIN'S MAGNITUDE DEPENDS ON THE RELATIVE MAGNITUDE OF THE INTEGRATED
C  ERROR -- IN THIS CASE, THE ERROR IS THE DIFFERENCE BETWEEN THE ACTUAL
C  THERMISTOR RESISTANCE AND THE DESIRED THERMISTOR RESISTANCE.
C
C  *****  NOTE:  THE SYSTEM HAS BEEN OBSERVED TO GO UNSTABLE WHEN TOO
C                HIGH OF A GAIN IS CHOSEN.
C
      WRITE(*,'(A)')'ENTER THE DESIRED FEEDBACK CONTROLLER GAIN
     +(5.00 IS A GOOD FIRST GUESS). '
      READ(*,'(F5.2)')CONST1
      WRITE(6,17)CONST1
 17   FORMAT('FEEDBACK GAIN SETTING:  ',F5.2)
      PRINT *,' '
      PRINT *,' '
      WRITE(*,'(A)')'ENTER RUN TIME (MINUTES) -- 0.5 IS A GOOD CHOICE. '
      READ(*,*)RUN_TIME
      PRINT *, ' '
      PRINT *, ' '
      RUN_TIME=RUN_TIME*60.0
      WRITE(6,20)RUN_TIME
 20   FORMAT('RUN TIME:  ',F5.2,1X,'SEC')
C
C  THE FOLLOWING LINES ARE INPUTS REGARDING THE DESIRED OPERATION
C  PARAMETERS OF HP 6186C DC CURRENT SOURCE.
      WRITE(*,'(A)')'ENTER THE FULL SCALE CURRENT, MA (EX. 5.000). '
      READ(*,*)RANGE
      PRINT *, ' '
      PRINT *, ' '
      WRITE(*,'(A)')'ENTER THE INITIAL CURRENT, MA (EX. 5.000). '
      WRITE(*,'(A)')'(USUALLY WANT THE FULL SCALE CURRENT AT T=0).'
      READ(*,*)CONTROL
      PRINT *, ' '
      PRINT *, ' '
      WRITE(6,30)CONTROL
 30   FORMAT('INITIAL CURRENT:  ',F6.3,1X,'MA')
      WRITE(6,31)RANGE
 31   FORMAT('FULL SCALE CURRENT:  ',F6.3,1X,'MA')
      CCONTROL=(CONTROL/RANGE)*999.0
      ICONTROL=INT(CCONTROL+0.5)
C  THE CONTROL WORD RECOGNIZED BY THE HP 59501B MUST BE
C  BETWEEN 2000 AND 2999.  THUS, A GIVEN RANGE CHOICE (THE SPAN)
C  IS DIVIDED INTO 999 INCREMENTS.
C
C  MAKING SURE THE FINITE LIMITS OF THE DIGITAL WORD ARE NOT
C  EXCEEDED.
      IF (ICONTROL .GT. 999) ICONTROL=999
      IF (ICONTROL .LT. 0) ICONTROL=0
      WORD=2000+ICONTROL
      WWORD=WORD*1.0
      CURRENT=CONTROL/1000.0
C  CURRENT IS IN TERMS OF AMPS.
C
C  THE VARIABLE ICONTR IS USED LATER IN THE CONTROL LOOP.
      ICONTR=ICONTROL
C
      WRITE(*,'(A)')'ENTER THE DESIRED DELTA OHMS (WITH RESPECT TO RECORDING
      DATA).'
      READ(*,*)DELTA_OHMS
      PRINT *, ' '
      PRINT *, ' '
      WRITE(*,'(A)')'ENTER THE DESIRED DELTA T -- SUGGEST 2.00 C.'
      READ(*,*)DELTA_T
      PRINT *, ' '
      PRINT *, ' '
      WRITE(6,40)DELTA_OHMS
```

```
   40 FORMAT('DELTA OHMS:  ',F4.1,1X,'OHMS')
      WRITE(6,50)DELTA_T
   50 FORMAT('DELTA T:  ',F2.0,1X,'C')
C
C  IEM FORTRAN77 VARIABLES ARE NOT EXACTLY IN THE SAME FORMAT AS THOSE
C  USED IN PASCAL.  SPECIFICALLY, THE FIRST CHARACTER OF A PASCAL STRING
C  MUST BE THE NUMBER OF CHARACTERS WITHIN THE STRING.  FOR EXAMPLE, THE
C  STRING VA1 HAS THREE CHARACTERS.  BUT, SINCE THE V IS IN POSITION
C  2, A LEADING BLANK HAS BEEN ALLOCATED BY THE NEXT STATEMENT.  THE
C  BLANK IS FILLED BY THE NUMBER 3 BY THE STR_1(1:1) ASSIGNMENT
C  IE., 4 - 1 = 3).  ALL OF THE STRINGS THAT ARE EXPORTED TO A PASCAL
C  MODULE -- LIKE THE COMMANDS TO THE HP 3497A AND THE HP 59501B --
C  MUST BE BUILT USING THESE SAME STEPS.  THE STRING STR_1 IS
C  ALWAYS USED AS THE OUTPUT STRING.
C
C  SET THE AUTOZERO FUNCTION OF THE HP 3497A TO ON.
      STR_1(2: )='VA1'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  MAKE THE THERMISTOR INITIAL RESISTANCE (=> TEMPERATURE) MEASUREMENT
C  FIRST TURN ON THE HP 3497A'S KNOWN CURRENT SOURCE.
C  NOTE:  THE VOLTAGE CARD IN SLOT 1 (STARTING FROM 0) HAS BEEN
C         CONFIGURED TO MAKE 4-WIRE RESISTANCE MEASUREMENTS.
      STR_1(2: )='VC1'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
      PAUSE '                 WAIT AT LEAST 2 SECONDS BEFORE CONTINUING
     +                                       '
      PRINT *, ' '
      PRINT *, ' '
C  CLOSING THE CHANNELS OF INTEREST
      STR_1(2: )='AC20,30'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
      CALL MY_READNUMBER(709,V_COLD)
C  THE ABOVE MAKES THE DESIRED VOLTAGE MEASUREMENT.  REFER TO THE
C  LISTING OF THE PASCAL PROGRAM HPIO.TEXT WHICH PERMITS THIS I/O
C  AND CONTAINS THE SUBROUTINES MY_WRITESTRINGLN AND MY_READNUMBER.
      R_COLD=V_COLD/1E-5
C  R_COLD IS THE THERMISTOR'S NONSELF-HEATED RESISTANCE IS OHMS.
      WRITE(*,60)R_COLD
   60 FORMAT('R_COLD =',F7.2,1X,'OHMS')
      WRITE(6,70)R_COLD
   70 FORMAT('COLD RESIST:  ',F7.2,1X,'OHMS')
C  TURNING OFF THE 10 MICROAMP CURRENT SOURCE OF THE HP 3497A.
      STR_1(2: )='VC0'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  PERFORMING AN ANALOG RESET FOR THE HP 3497A.
      STR_1(2: )='AR'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  THE FOLLOWING COMMAND PUTS THE 1000 OHM DUMMY RESISTOR IN-LINE.
      STR_1(2: )='DC4,1'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  CALCULATING THE INITIAL TEMPERATURE OF THE THERMISTOR
      T_COLD=AA+(BB*ALOG(R_COLD))
C  DETERMINING THE DESIRED ELEVATED TEMPERATURE FOR THE THERMISTOR.
      T_HOT=T_COLD+DELTA_T
C  BACKING OUT THE THERMISTOR RESISTANCE CORRESPONDING TO THIS
C  DESIRED ELEVATED TEMPERATURE.
      RT_FINAL=EXP(-((AA-T_HOT)/BB))
      WRITE(*,80)T_COLD
   80 FORMAT('T_COLD = ',F5.2,1X,'C')
      WRITE(*,90)T_HOT
   90 FORMAT('T_HOT = ',F5.2,1X,'C')
      WRITE(6,100)T_COLD
```

```
  100 FORMAT('COLD TEMP:  ',F5.2,1X,'C')
      WRITE(6,110)T_HOT
  110 FORMAT('HOT TEMP:  ',F5.2,1X,'C')
      WRITE(*,120)RT_FINAL
  120 FORMAT('RT_FINAL = ',F7.2,1X,'OHMS')
      WRITE(6,130)RT_FINAL
  130 FORMAT('DESIRED RESIST:  ',F7.2,1X,'OHMS')
C  BEGIN THE DATA COLLECTION ROUTINE
      PRINT *, ' '
      PRINT *, ' '
C  THE FOLLOWING LINE PUTS THE DESIRED INITIAL CURRENT ACROSSED
C  THE 1000 OHM DUMMY RESISTOR -- THIS ALLOWS THE CURRENT SOURCE
C  TO GET READY.
      CALL MY_WRITESTRING(706,WORD)
      CALL BEEP
      PAUSE 'READY   '
C  REFER TO THE HP 3497A QUICK REFERENCE SHEET FOR INFORMATION ON
C  THE FOLLOWING COMMANDS.
      STR_1(2: )='VA0'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
      STR_1(2: )='VR5'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
      STR_1(2: )='VD5'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
      STR_1(2: )='SD0'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  THE FOLLOWING COMMAND BRINGS THE THERMISTOR IN-LINE AND TAKES
C  THE DUMMY 1000 OHM RESISTOR OUT-OF-LINE.  THE INITIAL CURRENT
C  IS NOW SEEN BY THE THERMISTOR.
      STR_1(2: )='DC4,0'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  SETTING THE SYSTEM RUN CLOCK TO ZERO
      CALL SETSYSTIME(0)
C  INNER LOOP:  MEASURE VT AND CALCULATE R_HOT
C  MY_READNUMBER IS A PASCAL SUBROUTINE THAT MEASURES AND RETURNS
C  THE THERMISTOR VOLTAGE.
 135  CALL MY_READNUMBER(709,VT)
C  CHECKING THE CLOCK AND COUNTING THE NUMBER OF VOLTAGE MEASUREMENTS
C  THAT ARE BEING MADE DURING THE RUN.
      TTIME=SYSCLOCK()/100.
      ILOOP=ILOOP+1
      R_HOT=VT/CURRENT
C
C                INTEGRAL CONTROL STRATEGY
C
C  THE DIFFERENCE IN THE THERMISTOR'S RESISTANCE ACTS AS THE FEEDBACK
C  ERROR.  RT_FINAL IS THE DESIRED RESISTANCE SETTING.
      ERROR_R=(R_HOT-RT_FINAL)
C  THE NEXT LINE IS MOST APPLICABLE DURING THE INITIAL START-UP.  IT
C  HELPS THE SYSTEM TO NOT HAVE AS GREAT AN OVERSHOOT OF THE DESIRED
C  RESISTANCE.  YOU WANT THE CURRENT TO GO DOWN AS SOON AS THE DESIRED
C  RESISTANCE IS REACHED; YOU DON'T WANT A LAG CAUSED BY AN INTEGRATION
C  OF A POSITIVE FEEDBACK ERROR.  THE CONTROLS PEOPLE REFER TO THIS
C  PROBLEM AS INTEGRATOR WINDUP.
      IF (ICONTR .GE. 999 .AND. ERROR_R .GT. 0.0) GOTO 200
      IF (ICONTR .LE. 0 .AND. ERROR_R .LT. 0.0) GOTO 200
C  INTEGRATING THE FEEDBACK ERROR
      ERROR_INT=ERROR_INT+ERROR_R
C  ICONTROL IS A REFERENCE STATE CORRESPONDING TO THE INITIAL
C  CONTROL WORD, USUALLY 999 -- THE LEADING 2 IS ADDED LATER.
  200 ICONTR=INT(ICONTROL+(CONST1*ERROR_INT+0.5))
C  THE FOLLOWING LINES MAKES SURE THAT THE MAX VALUE OF 999 AND
C  THE MIN VALUE OF 0 ARE NOT EXCEEDED.
```

```
      IF (ICONTR .GT. 999) ICONTR=999
      IF (ICONTR .LT. 0) ICONTR=0
      WORD=2000+ICONTR
      WWORD=WORD*1.0
C  DETERMINING THE CURRENT BEING SENT TO THE THERMISTOR.  RECALL,
C  THE CURRENT IS KNOWN; IT IS NOT MEASURED; YOU ARE CONTROLLING IT.
      CURRENT=ICONTR*(RANGE/999.)/1000.
      CALL MY_WRITESTRING(706,WORD)
C  DETERMINING IF THE DATA FOR THIS OBSERVATION SHOULD BE STORED.
      DELTA=ABS(RT_FINAL-R_HOT)
      COUNT=COUNT+1
      IF (COUNT .GT. 1200) CALL TERMINATE
      VT_TIME(COUNT,1)=1/((1000*TTIME)**.5)
      VT_TIME(COUNT,2)=VT**2
      VT_TIME(COUNT,3)=R_HOT
      VT_TIME(COUNT,4)=1000.*CURRENT
      VT_TIME(COUNT,5)=WWORD
      VT_TIME(COUNT,6)=TTIME
      IF (TTIME .GT. RUN_TIME) CALL TERMINATE
C  IF THE SUBROUTINE TERMINATE HAS BEEN CALLED, THEN FLAGG WILL BE
C  SET TO 1, AND THE PROGRAM WILL STOP TAKING DATA.
      IF (FLAGG .EQ. 0) GOTO 135
      PRINT *, ' '
      PRINT *, ' '
      PRINT *, ' '
      CALL BEEP
      PRINT *, '     *****   FINISHED   *****'
      END

      SUBROUTINE TERMINATE
C  THIS SUBROUTINE IS USED TO STOP THE TEST RUN AND GIVE THE OPERATOR
C  THE OPTION OF PRINTING AND/OR STORING THE DATA.
      INTEGER COUNT,ILOOP,I,ANSWER,FLAGG,WORD
      CHARACTER*81 STR_1
      COMMON /BLOCK1/ WWORD,COUNT,TTIME,VT,R_HOT,CURRENT,AA,BB
      COMMON /BLOCK2/ ILOOP,FLAGG
      COMMON /BLOCK3/ VT_TIME(1200,6)
C  TURNING THE CURRENT SUPPLY TO ZERO OUTPUT.
      WORD=2000
      CALL MY_WRITESTRING(706,WORD)
C  THE FOLLOWING DISCONNECTS THE HP 3497A DVM FROM THE CIRCUIT
C  THIS IS NEEDED SINCE A SINCE A LONE VOLTAGE MEASUREMENT IS
C  BEING MADE AT THE PORT OF THE DVM.
      STR_1(2: )='DO4,1'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
C  TAKING THE THERMISTOR OUT-OF-LINE AND PUTTING THE 1000 OHM
C  RESISTOR BACK IN-LINE.
      STR_1(2: )='DO4,0'
      STR_1(1:1)=CHAR(LEN(STR_1)-1)
      CALL MY_WRITESTRINGLN(709,STR_1)
      PRINT *,' '
      WRITE (*,220) TTIME
  220 FORMAT('TIME = ',F5.2,' SEC')
      CPS=ILOOP/TTIME
      PRINT *,' '
      WRITE(6,230) CPS
  230 FORMAT ('READINGS PER SECOND:  ',F5.2)
      PRINT *,' '
      PRINT *,' '
      CALL MY_CLEAR(709)
      CALL MY_CLEAR(706)
      WRITE(6,300)TTIME
 300  FORMAT('ELAPSED TIME:  ',F7.2,1X,'SEC')
      WRITE(6,310)COUNT
 310  FORMAT('VALUES RECORDED:  ',I4)
      WRITE (6,*)' '
C
```

```
C  OPPORTUNITY TO PRINT THE PERTINENT DATA
C
      WRITE(*,'(A\)')'DO YOU WISH TO PRINT THE DATA (1 ==> Y OR
     +2 ==> N)?     '
      READ(*,*)ANSWER
      IF (ANSWER .EQ. 2) GOTO 500
      WRITE(6,320)
 320  FORMAT('1/(TIME**.5)',6X,'(VT_HOT)**2',6X,'RT_HOT',6X,'CURRENT',
     +6X,'CONTROL',6X,'TIME')
      WRITE(6,330)
 330  FORMAT('1/(MSEC**.5)',9X,'V**2',11X,'OHMS',9X,'MA',10X,
     +'WORD',8X,'SEC')
      WRITE (6,*)' '
      DO 400, I=1, COUNT
      WRITE(6,350)VT_TIME(I,1),VT_TIME(I,2),VT_TIME(I,3),
     +VT_TIME(I,4),VT_TIME(I,5),VT_TIME(I,6)
 350  FORMAT (2X,F6.5,9X,F8.4,6X,F8.2,7X,F5.3,8X,F5.0,6X,F6.3)
 400  CONTINUE
 500  PRINT *, ' '
      PRINT *, ' '
      WRITE(*,'(A)')'DO YOU WISH STORE THE DATA ON A DISC'
      WRITE(*,'(A\)')'(1 ==> Y, 2 ==> N)?  '
      READ(*,*)ANSWER
      IF (ANSWER .EQ. 2) GOTO 600
C
C   STORING THE DATA TO THE DATA DISK IN DRIVE #4.
C
      WRITE (*,510)
 510  FORMAT(60(/))
      PRINT *, 'BEFORE PROCEEDING YOU MUST BE SURE THAT THE DATA FILE'
      PRINT *, 'NAMED THD: VTT HAS BEEN FIRST CONVERTED TO ITS ASCII'
      PRINT *, 'EQUIVALENT VIA THE TRANSLATE OPTION WITHIN THE FILER'
      PRINT *, 'AND THEN REMOVED USING THE SAME FILER.'
      PRINT *, ' '
      PRINT *, ' '
      PAUSE
      WRITE (*,510)
      PAUSE  '          *****  PLACE THE DATA DISKETTE IN DRIVE #4  ***** '
      WRITE(*,511)
 511  FORMAT(66(/))
      PRINT *, 'WRITING . . . .'
      OPEN(UNIT=5,FILE='THD: VTT',STATUS='NEW')
C  THE DATA DISC MUST HAVE A VOLUME LABEL OF THD IN ORDER FOR THE
C  STORING PROCESS TO BE SUCCESSFUL.  THD STANDS FOR THERMISTOR DATA.
      NEND3=3*COUNT
C  NEND3 IS THE TOTAL NUMBER OF VALUES TO BE STORED.
      WRITE(5,513)NEND3
 513  FORMAT(I5)
C  STORING THE THE SQUARED THERMISTOR VOLTAGES.
      DO 520, I=1,COUNT
      WRITE(5,515)VT_TIME(I,2)
 515  FORMAT(F8.4)
 520  CONTINUE
C  STORING THE SELF-HEATED TEMPERATURES OF THE THERMISTOR.
      DO 530, I=1,COUNT
      TEMP=AA+BB*ALOG(VT_TIME(I,3))
      WRITE(5,525)TEMP
 525  FORMAT(F6.2)
 530  CONTINUE
C  STORING THE TIMES (IN SECONDS) WHEN THE MEASUREMENT WERE MADE.
      DO 540, I=1,COUNT
      WRITE(5,535)VT_TIME(I,6)
 535  FORMAT(F6.2)
 540  CONTINUE
 600  FLAGG=1
      RETURN
      END
```

```
MODULE HPIO;
{  THIS PROGRAM IS WRITTEN USING HP PASCAL 3.0.  THE PROGRAM CONTAINS
   THE SUBROUTINES THAT ALLOW THE IEM FORTRAN77 PROGRAMS TO INTERFACE
   WITH THE HP DATA ACQUISITION AND CONTROL EQUIPMENT.  HP PASCAL HAS
   SPECIAL COMMANDS THAT PERMIT THE I/O. }
$SEARCH 'V11:IO.','V11:INTERFACE.'$
{  THE DOLLAR SIGNS INDICATE THAT THE SEARCH COMMAND IS A
   COMPLIER DIRECTIVE.}
IMPORT GENERAL_2,HPIB_2,IODECLARATIONS;
{  THIS PASCAL PROGRAM UTILIZES MODULES FOUND ON THE FILES IO AND
   INTERFACE.  THESE FILES, IN TURN, ARE PART OF THE IEM LIBRARY
   (VERSION 3125).  REFER TO PAGE 4-2 OF THE IEM FORTRAN77 MANUAL
   FOR MORE INFORMATION ON WHICH MODULES MAKE UP THE TWO FILES.
   UPON REVIEWING THE AVAILABLE HP PASCAL LIBRARY MODULES, I FIND
   THAT THE SAME MODULES EXIST.  I NEVER TRIED TO VERIFY THAT THE
   IEM AND HP MODULES ARE THE SAME.  REFER TO PAGES 6,7, AND THE
   CHAPTER ENTITLED INTRODUCTION TO I/O IN THE PASCAL 3.0
   PROCEDURE LIBRARY MANUAL FOR MORE INFORMATION.}
EXPORT
{  THE EXPORT COMMAND STATES THAT THE FOLLOWING TYPES AND PROCEDURES
   MAY BE IMPORTED BY OTHER PROGRAMS (LIKE THERMSC).}
    TYPE STRING80 = STRING[80];
        PROCEDURE MY_WRITESTRINGLN(DEV:INTEGER;STR:STRING80);
        PROCEDURE MY_TRIGGERV(DEV:INTEGER);
        PROCEDURE MY_WRITESTRING(DEV:INTEGER;VAR A:INTEGER);
        PROCEDURE MY_READNUMBER(DEV:INTEGER;VAR A:REAL);
        PROCEDURE MY_CLEAR(DEV:INTEGER);
{  THE MY_ PREFIX IS OFTEN USED TO MAKE A COMMAND INTO A SUBROUTINE
   (IE., A PROCEDURE).  THE PROCEDURES CAN BE NAMED ANYTHING
   THAT HELPS THE PROGRAMMER RECOGNIZE WHAT IT DOES.  THE DEV
   VARIABLE STANDS FOR THE HP ADDRESS CODE.  FOR EXAMPLE, THE
   HP 3497A IS 709 WHILE THE HP 59501B IS 706.  ALL OF THE
   PROCEDURES MUST AGREE WITH THE FORTRAN77 PROGRAM THAT CALLS
   THEM WITH RESPECT TO THE NUMBER AND ORDER OF THE VARIABLES
   AND/OR STRINGS PASSED FROM ONE TO THE OTHER.}
IMPLEMENT
{  FOR MORE INFORMATION ON ALL THE I/O COMMANDS DEFINED BELOW,
   REFER TO THE PASCAL 3.0 PROCEDURE LIBRARY MANUAL, ESPECIALLY
   THE FOLD-OUT PAGES OF THE REFERENCE SECTION (P. 305).}
        PROCEDURE MY_WRITESTRINGLN;
        BEGIN
        WRITESTRINGLN(DEV,STR);
{  WRITESTRINGLN OUTPUTS THE STRING, A CARRIAGE RETURN, AND A
   LINE FEED.}
        END;
        PROCEDURE MY_TRIGGERV;
{  THIS PROCEDURE IS NOT USED IN THE FINAL VERSIONS OF THE THERMISTOR
   THERMAL CONDUCTIVITY TEST PROGRAMS BECAUSE THE THERMISTOR'S
   VOLTAGE IS READ AT THE EXTERNAL PORT OF THE DVM.  THIS PROCEDURE
   WAS UTILIZED WHEN THE THERMISTOR WAS CONNECTED TO CHANNEL 09.}
        VAR
        FMT: STRING[80];
        BEGIN
        FMT: ='AI09';
{  AI IS A COMMAND RECOGNIZED BY THE HP 3497A.  AI, WHICH STANDS FOR
   ANALOG INPUT, CLOSES THE DESIRED CHANNEL AND TRIGGERS THE DVM TO
   TAKE A MEASUREMENT.}
        WRITESTRINGLN(DEV,FMT);
        END;
        PROCEDURE MY_WRITESTRING;
{  THE MOST IMPORTANT PROCEDURE.  THIS PROCEDURE BUILDS THE DIGITAL
   WORD THAT REPRESENT THE DESIRED CURRENT TO BE OUTPUTTED BY THE
   COUPLED HP 59501B AND HP 6186C.  THE WORD BUILDING CONSISTS OF
   TAKING A TYPICAL NUMBER LIKE 2999 AND BUILDING A STRING BY
   ASSIGNING, IN ORDER AND ONE AT A TIME, THE 2, THE 9, THE 9, AND
   THE LAST 9.}
        VAR
        FMT: STRING[80];
        ST: INTEGER;
        NX: INTEGER;
        RESULT: INTEGER;
        BEGIN ON
        FMT: = '    ';
        ST: = 1;
{  ST DESIGNATES THE FIRST POSITION IN THE STRING FMT.}
        RESULT: = A DIV 1000;
{  BY USING DIV, RESULT IS EQUAL TO THE FIRST NUMBER OF THE DIGITAL
   WORD (EG., 2)}
        STRWRITE(FMT,ST,NX,RESULT: 1);
{  STRWRITE IS A TYPICAL PASCAL COMMAND THAT WRITES THE 2 INTO THE
   DESIGNATED POSITION WITHIN FMT.  REFER TO PAGE 202 OF THE HP
   PASCAL LANGUAGE REFERENCE FOR MORE INFORMATION.}
        ST: = NX;
        A: = A-RESULT*1000;
{  THE PREVIOUS CALCULATION GETS RID OF THE LEADING NUMBER (EG.,
   2999 BECOMES 999) AND THE PROCESS STARTS AGAIN.}
        RESULT: = A DIV 100;
        STRWRITE(FMT,ST,NX,RESULT:1);
        ST: = NX;
        A: = A-RESULT*100;
        RESULT: = A DIV 10;
        STRWRITE(FMT,ST,NX,RESULT: 1);
        ST: = NX;
        A: = A-RESULT*10;
        RESULT: = A DIV 1;
        STRWRITE(FMT,ST,NX,RESULT: 1);
        WRITESTRING(DEV,FMT);
{  ONCE THE STRING FMT IS BUILT, WRITESTRING SENDS THE SPECIFIED
   STRING TO THE SPECIFIED DEVICE.}
        END;
        PROCEDURE MY_READNUMBER;
        BEGIN
        READNUMBER(DEV,A)
{  READNUMBER PERFORMS A FREE FIELD NUMERIC ENTRY FROM THE SPECIFIED
   DEVICE.}
        END;
        PROCEDURE MY_CLEAR;
        BEGIN
        CLEAR(DEV);
{  CLEAR ATTEMPTS TO SEND A FORM OF THE CLEAR MESSAGE TO THE
   SPECIFIED DEVICE(S).}
        END;
END.
```

```
10        THIS PROGRAM TAKES THE ASCII DATA FILE DEVELOPED FOLLOWING
20        THE V**2 VERSUS 1/(t**.5) CALIBRATION STEP AND CONVERTS IT
30        INTO A BDAT FILE THAT IS READILY UPLOADED INTO THE BASIC
40        STATISTICS PACKAGE.
50
60        THIS PROGRAM IS STORED UNDER THE FILENAME:  CONVERSION.
70
80        THIS PROGRAM WAS WRITTEN USING HP BASIC 3.0.
90
100   DIM X(2200),XX(2200)
110   PRINT "    AT THIS TIME, PLACE THE DATA DISK WITH THE ASCII SOURCE DATA FILE"
120   PRINT "    IN THE RIGHT-HAND DISC DRIVE, #3."
130   PRINT " "
140   PRINT "    ALSO, PLACE THE THE DATA DISC WHICH WILL STORE THE BDAT EQUIVALENT"
150   PRINT "    DATA FILE IN THE LEFT-HAND DRIVE, #4."
160   PRINT " "
170   PRINT " "
180   PRINT "    PRESS <CONTINUE> WHEN READY"
190   PAUSE
200   PRINT " "
210   PRINT " "
220   PRINT " "
230   PRINT " "
240   PRINT "    WOULD YOU LIKE TO CATALOG EITHER DISK TO SEE WANT FILES PRESENTLY EXIST?"
250   INPUT "    ENTER EITHER THE DESIRED DISC DRIVE NUMBER (3 OF 4) OR 0 TO CONTINUE.  ",NDR
260   PRINT " "
270   PRINT " "
280
290       CATALOGING THE CONTENTS OF THE DISC IS DRIVE #3.
300   IF NDR=3 THEN
310   CAT ": INTERNAL"
320   PRINT " "
330   PRINT " "
340   PRINT " "
```

```
350  GOTO 240
360  END IF
370
380     CATALOGING THE CONTENTS OF THE DISC IN DRIVE #4.
390  IF NDR=4 THEN
400  CAT ":INTERNAL,4,1"
410  PRINT " "
420  PRINT " "
430  PRINT " "
440  GOTO 240
450  END IF
460  PRINT " "
470  PRINT " "
480  PRINT " "
490
500     PRINTING THE 12TH ASCII CHARACTER, A FORM FEED --> ACTS LIKE A
510     CLEAR SCREEN COMMAND.
520  PRINT CHR$(12)
530  INPUT "ENTER THE FILENAME OF THE ASCII SOURCE DATA FILE (EX. 9CAS_1A___)  ",M$
540  PRINT " "
550  PRINT " "
560  PRINT "ENTER THE FILENAME OF THE BDAT EQUIVALENT DATA FILE"
570  PRINT "(SUGGESTION:  USE THE SAME FILENAME AS ABOVE, IE. ";M$;")."
580  INPUT N$
590
600     DESIGNATING DRIVE #4 AS THE DEFAULT DRIVE.
610  MASS STORAGE IS ":INTERNAL,4,1"
620
630     ALLOCATING SPACE ON THE DATA DISC IN DRIVE #4 FOR A NEW FILE.
640  CREATE BDAT N$,70,256
650
660     HAVE TO GIVE EACH I/O FILE NAME A CORRESPONDING PATH NAME.
670  ASSIGN @PATH1 TO N$
680
```

```
690       DESIGNATING DRIVE #3 AS THE DEFAULT DRIVE.
700    MASS STORAGE IS ":INTERNAL"
710    ASSIGN @PATH2 TO M$
720
730       THE FIRST DATA VALUE (NEND) IS THE TOTAL NUMBER OF DATA VALUES
740       IN THE ASCII FILE.
750       ENTERING IN THE DATA FROM THE DATA FILE WITH THE CORRESPONDING
760       PATH NAMED PATH2.
770    ENTER @PATH2;NEND
780
790       READING THE DATA FROM THE SOURCE (ASCII) DATA FILE
800
810    PRINT CHR$(12)
820    PRINT "     READING . . . . APPROXIMATELY A MINUTE"
830    FOR I=1 TO NEND
840    ENTER @PATH2;X(I)
850    NEXT I
860
870       CLOSING THE I/O PATH.
880    ASSIGN @PATH2 TO *
890       CHR$(12) IS THE ASCII CHARACTER FOR A FORM FEED -- CLEARS THE SCREEN
900    PRINT CHR$(12)
910
920       WRITING THE DATA TO THE NEW (BDAT) FILE.
930    PRINT "    WRITING . . . . "
940    MASS STORAGE IS ":INTERNAL,4,1"
950       OUTPUTTING THE ARRAY OF DATA ALL AT ONCE.
960    OUTPUT @PATH1;X(*)
970
980       CLOSING THE I/O PATH.
990    ASSIGN @PATH1 TO *
1000   PRINT CHR$(12)
1010
1020   PRINT " "
```

```
1030  PRINT " "
1040  PRINT "     *****     FINISHED     *****"
1050  PRINT " "
1060  PRINT " "
1070
1080     PRINTING INFORMATION THAT FURTHER AIDS THE DATA REDUCTION SEQUENCE.
1090  NN=NEND/3
1100  FOR I=1 TO 2
1110  PRINT " "
1120  PRINT " "
1130  PRINT USING 19A,2X,10A;"BDAT DATA FILENAME: ",N$
1140  PRINT " "
1150  PRINT "THREE VARIABLES WERE STORED:  V**2 (V**2), T_SELF-HEAT (C), TIME (SEC)"
1160  PRINT " "
1170  PRINT "TOTAL NUMBER OF OBSERVATIONS (FOR STATISTICAL DATA REDUCTION) = ";NN
1180  PRINT " "
1190  PRINT " "
1200
1210     PRINTING THE PERTINENT DATA TO THE HP PRINTER (701) AND THE CRT (1).
1220  PRINTER IS 701
1230  NEXT I
1240
1250  PRINTER IS 1
1260  MASS STORAGE IS ":INTERNAL"
1270  END
```

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A transient technique was validated for making thermal conductivity measurements. The technique incorporated a small, effectively spherical, heat source and temperature sensing probe. The actual thermal conductivity measurements lasted 30 seconds. After approximately 15 minutes of data reduction, a value for thermal conductivity was obtained. The probe yielded local thermal conductivity measurements. Spherical sample volumes less than 8 cm^3 were required for the materials tested. Thermal conductivity (and moisture) distributors can be measured for relatively dry or wetted samples.

The technique employs an encapsulated bead thermistor. A thermistor, more commonly used as a temperature transducer, has the inherent feature of being readily self-heated. A computer-based data acquisition and control system regulates the power supplied to the thermistor such that its self-heated temperature response approximates a step change. Thermal conductivity is deduced from the transient measurement of the power dissipated by the probe as a function of time.

The technique was used to measure the thermal conductivity of fifteen liquids and five insulation materials. Two different thermistors types, glass-encapsulated and teflon-encapsulated, were evaluated. Capabilities and limitations of each probe type and the measurement technique, in general, were observed.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

calibrated probe; encapsulated bead thermistor; insulation; liquids, thermal conductivity; transient measurement

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